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Phase II: Fire Extinguishment by Electro-Magnetic Fields

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Abstract

This report describes a Phase II effort that demonstrated the technological feasibility to extinguish fires using an electromagnetic (EM) pulse. Using this technology only electrical energy is used for the fire extinguishment process; no water or chemical are required. The experimental device employed 10 energy storage capacitors of 40 μF total and operated at 15 kV. With this device, heptane, diesel and kerosene pool fires, as well as forced-flow flames of propane and butane were extinguished. The facility can be used to study extinguishment of already ongoing fires as well as to study explosion mitigation. In addition, a specialized version for the latter application was designed, built and tested (0.5 μF at 35 kV). There are some fire extinguishment methods, which employ electrostatic fields. In contrast to these methods, the present device employs an electromagnetic (EM) pulse. The duration of this EM pulse is only several microseconds. Pulse rise times of less than 100 nanoseconds have been achieved. The present process is the only practical process known to date for extinguishment of fires without a chemical agent. It is also the only process known at present that is fast enough to be considered for use in explosion mitigation applications.

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Preface

This report was prepared by Schneider Laboratories, Ltd., 1663 Technology Avenue, Alachua, Florida 32615, under Contract No. F33615-97-C-5646, for the Department of the Air Force, Wright Laboratory WL/MLKN Bldg. 7, 2530 C St., Wright-Patterson AFB, OH 45433-7607.

This final report describes the results of experiments aimed at determining if enhanced fire extinguishing capabilities or explosion mitigation could be realized using electromagnetic pulses. To this end, the goal was to determine the effect of electromagnetic pulses on fire extinguishment and explosion mitigation.

This work was performed between 2 July 1997 and 30 September 2000. AFRL/MLQD project engineer was Dr. Juan Vitali.

Executive Summary

A. General

The idea to extinguish fires using an electromagnetic (EM) pulse was explored with some preliminary experiments. A proposal for a Phase I effort, which was based on the success of these experiments, was produced and funded. The objective of this Phase I effort was to demonstrate scientific feasibility of this idea. This objective was achieved.

Ordinarily one would go on and perform basic research to understand the extinguishment mechanism(s) so that one could construct a mathematical model to predict the performance of applied versions of the experimental device. Considering the complexity of the combustion process and the EM pulse dynamics, this will certainly be a monumental effort.

Considering this and considering the uncertainty as to whether or not this process may be scaleable to commercial sizes, it was decided to demonstrate the scalability before trying to understand the extinguishment process more completely. Nevertheless, some research toward understanding of the extinguishment process was performed in order to optimize the design of the prototype to be built for the present Phase II effort. However, this needs to be classified as applied research.

In addition, at the time when the decision to scale up the experimental device (Phase I) was made, it was not clear what the final application of this process would be: fire extinguishment or explosion mitigation. To do the basic research for both would have meant an even larger effort, which could not be justified unless scalability has been established. Moreover, it was felt that the experimental device could be scaled up by a factor of 10 without having a firm grasp of all of the chemical and electrodynamic factors involved.

B. Accomplishments of Phase II

The experimental device (Phase I) employed an energy storage capacitor of 450 joules (4 μF at 15 kV). This was sufficient to extinguish a heptane pool fire having an area 30 cm^2 . The facility built for Phase II has ten times the energy storage capacity of the Phase I experiment.

A scale-up by a factor of 10 can be considered adequate to go from an experiment to a prototype. As it stands, the completed Phase II facility can be used as is to study extinguishment of already ongoing fires as well as to study explosion mitigation. In addition a specialized version for the latter application was designed, built and tested (0.5 μF at 35 kV).

With the prototype developed under the present effort, several kinds of fires have been extinguished. These were heptane, diesel and kerosene pool fires, as well as forced-flow flames of propane and butane.

There are some already existing fire extinguishment methods, which employ electrostatic fields. In contrast to these established methods, the device developed in the present effort employs an electromagnetic (EM) pulse. The duration of this EM pulse is only several microseconds. Pulse rise times of less than 100 nanoseconds have been achieved. This device is capable of producing a power of approximately 4.5 gigawatts during the rise time of the discharge current.

Fire extinguishment by an electromagnetic pulse was demonstrated and practiced for the first time by the present effort. In this process neither water nor any other chemical extinguishment agent was used. We submit that the present process is the only practical process for extinguishment of fires without a chemical agent. It is also the only process known at present that is fast enough to be considered for use in explosion mitigation applications.

C. The Design

The term EM pulse is used to describe a high intensity burst of electromagnetic radiation. Such a pulse can be generated by electrical means. For application to fire extinguishment, it is tacitly implied that such a pulse needs to travel through the air rather than being transported by wires.

For the creation of such a pulse, electrical energy needs to be stored and then released as fast as possible. Electrical energy can be stored capacitively or inductively. However, for fast release of the stored energy, capacitive storage is preferred. For this reason, a capacitor discharge mechanism was chosen. Such technology is well understood, and therefore need not to be discussed here. The innovation, that the present Phase II effort added, is the design of the antenna that emits the EM pulse. This antenna does more than just emit the EM pulse, it also shapes this pulse. This shall be explained briefly in the following.

As it is well known, a collapsing magnetic field will generate an electric field and vice versa. The collapse of these fields can occur very rapidly, the velocity of light in vacuum being the limitation. The challenge is to interrupt an existing field fast enough to cause such a collapse. For a collapsing magnetic field the induction law

$$d\Phi/dt = -U_{ind} \quad \Phi: \text{mag. flux} ; \quad U: \text{induced voltage}$$

is valid. This means that the faster a magnetic field can be interrupted, the larger the induced voltage will be, voltage meaning the potential difference between two given points in the resulting electric field. This interruption is accomplished by the antenna, designed in the present effort, as will be explained in brief detail below.

While in the present device an existing magnetic field is interrupted, one could also interrupt an existing electric field rapidly as well. An example of this is the Blumlein circuit, which was developed during the early stages of radar development and is still used today for the atmospheric pressure nitrogen laser.

The antenna designed in the present effort is shaped in the form of a coil. It is a continuous winding in a spiral fashion of a copper wire. This coil is attached to the capacitor via a spark gap. When the spark gap is fired, the current in the coil will ring according to the laws of electrodynamics in a resistor-inductor-capacitor (RLC) circuit. The current rise time is moderate and no fire extinguishment takes place. However, when the coil is cut at a certain location, having now a small gap (1 to 5 mm), the situation changes dramatically. If the coil is now fired (still via the main spark gap) a different current trace is observed. The current rise time is now considerably shorter and the damping of the observed electromagnetic wave is stronger. Fire extinguishment now takes place. Due to the creating of a gap in the antenna coil, the interruption of the magnetic field is now faster creating a much stronger electric field.

This metamorphosis can be explained by the observation that, due to the high voltage applied, the gap in the coil is jumped by the current coming out of the capacitor and an arc is so formed. The current through this arc is on the order of tens of kiloamperes. The magnetic field of the coil is parallel to the axis of the coil and the current through the arc is perpendicular to the axis, consequently a $j \times B$ situation exists. This creates a force that blows the arc (or rather its charge carriers) away, out of the gap. Obviously, this is a new way to achieve an ultra fast current interruption (and therefore magnetic field interruption) with a minimum of inductance and a minimum of circuit elements (klystrons etc.)

This type of arc occurs as a special type of gas discharge. Ordinarily one calls a low voltage, high current discharge an arc, while a spark is a high voltage, low current discharge. The "arc" in question has both, a high voltage and a high current. In the older literature, this is sometimes called an "arc spark."

D. Extinguishment Mechanisms

It is known that both electric and magnetic fields can influence flames. In the case of the present effort, whether it is the magnetic field or the electric field that directly or indirectly achieves the extinguishment is not obvious. In the following we list some experimental evidence that might shed some light on the extinguishment mechanism.

a. Spectroscopic Evidence: The discharge through the gap in the coil produces a plasma that emits a high intensity light pulse. The phenomenon exists during the first two periods of the current. The light intensity is about a million times brighter than the flame to be extinguished. The spectrum of this light pulse shows strong emissions of copper atoms, as well as some atomic emission of nitrogen and oxygen. Also emission of ions of these elements are present. The only molecular bands that were detected are CN bands. The carbon source for the CN could be the material (epoxy) of the substrate that holds the bare copper wire of the coil. Since this is a high pressure plasma, electron temperature and heavy particle temperature can not be far apart. Judging by the presence of copper II emission from this plasma one can say that the electron temperature should be between 20,000 K and 30,000 K. One could measure the temperature more precisely with the line ratio method, but for the purposes of this effort it is sufficient to state that there is a plasma consisting of atoms and ions. The CN bands obviously come from the parts

of the coil body that are adjacent to the arc. Damage to the coil substrate attest to that. The enthalpy of a plasma is minuscule. Therefore its temperature drops drastically when contacting solid state material; but it can evaporate or ablate material with which it comes into contact. The ablated carbon, however, must be of low temperature, consequently the suspicion is that the CN molecules are formed by chemical excitation.

The plasma may be created by thermal means (heavy particle collisions), although that should not mean that it can be assumed that even local thermodynamic equilibrium is established. In view of the short times involved the term "temperature" should be used with discretion.

b. Integral Light: IR detectors and UV detectors, having sub-microsecond rise-times, were used to measure the lifetime of the light phenomenon. There are basically two light pulses present, one during the first current period and a second one during the second current period. Still photography shows that the plasma extends up to 10 cm out in front of the coil.

c. Acoustic Phenomena: The discharge is accompanied by a loud acoustical phenomenon. The speed of this phenomenon was measured to be on the order of the speed of sound or slightly supersonic. There is also air movement present (air flow), which travels considerably slower than the sound.

d. Preliminary Conclusions on Extinguishment: If the plasma would extend all the way to the flame, one could conclude that the flame becomes dissociated and the combustion kinetics are disrupted during the EM pulse. Flame combustion would then terminate if energy required to maintain the chain reaction would be radiated away. However there is no evidence that the plasma extends all the way to the flame. Instead we suspect that the electric field interacts with the flame and causes extinguishment.

Analyzing the oscilloscope current traces one observes that the current achieves its first maximum before the first 100 nanoseconds are over. However light emissions persist up to 3 complete periods. Some of the light may be coming from the flame but most of it is emitted by the plasma. The first 3 periods are strongly damped. If there is still a 4th and 5th period, no extinguishment takes place.

We submit that the presence of a large electric field is necessary for extinguishment. The electric field would need to accelerate and multiply the few electrons present in the flame, which in turn would cause molecules or even atoms to radiate the energy that is normally used to form the next generation of free radicals or other endothermic reactions required to continue the chain reaction. Electrons are considerably faster than heavy particles and radiation is considerably faster than energy transportation by heavy particle collisions (heat conduction). The fact that fast rise times are required for extinguishment forces us to conclude that fast processes are responsible for extinguishment.

Therefore, if this reasoning is correct, one would have to state that the flame is extinguished by radiation cooling.

Section I. Introduction

There are many ways to extinguish fires. Why continue to search for other ways?

All known fire extinguishment methods require an extinguishing agent. The most widely used is water, but there is also sand, foam and aerosols. Many fires, but by no means all, will always be extinguished with water. However some fires cannot be extinguished with water or in some instances water causes too much damage itself. Aerosols and foam are, in general, specific for a certain class of fires; and therefore, they might not be at hand for the ongoing fire. Some foams and aerosols have environmental problems and their use is being phased out.

As a consequence of the above mentioned facts, there is indeed a need to search for alternate fire extinguishment methods, particularly one that does not need an extinguishment agent. The effort reported in this document was an attempt to find such an agentless fire extinguishment method. As one can see from this report such a method has been found. This method uses only the effects of an electromagnetic pulse (EM pulse).

The results of the Phase I effort indicated that it is possible to extinguish a heptane pool fire with an electromagnetic pulse (EM pulse). At that point in time the extinguish mechanism was not clear. Neither was it obvious whether the phenomenon was scaleable to a fire larger than the one extinguished in the Phase I effort.

For the present effort it was proposed to build a prototype EM pulse fire extinguishment device that represented a scale-up of the Phase I experiment by a factor of 10. The Phase I experiment utilized a 4 μF capacitor; therefore, the prototype developed here requires a capacitance of 40 μF .

The design of a scaled-up device would have required too many assumptions, some of them being even speculative. For this reason we built a pre-prototype to explore certain parameters. Results gained operating the pre-prototype can be found in the "Section III. Operation of Device." Based on the results gained with the pre-prototype it was decided to build ten individual units having a capacity of 4 μF each, rather than build one single large unit of 40 μF .

In the “Section II. Description of Device” the design and physical structure of the final prototype is provided. In “Section VI. Extinguishment Mechanism” an attempt is made to explain the mechanism that extinguishes the fire. However, this explanation is speculative as know significant effort could be expended to completely understand all of the factors involved, therefore, this should be understood as an initial attempt. The effort described here was not a basic research effort, but a development effort that had the goal of building a device that extinguishes a fire with an electromagnetic pulse (EM pulse), without the use of water or any chemical.

Before such a device was demonstrated, there was no way to do basic research concerning a mechanism that was at that time not known to exist. Since the demonstration has been successfully accomplished, now it may be appropriate to do basic research concerning the extinguishment mechanism. In the “Section VIII. Conclusions and Recommendations” recommendations are made as to what type of experiments should be done to get more insight into the extinguishment mechanism. In the same section also, possible applications of the new technology are discussed.

Section II. Description of Device

1. Mechanical Design

Although this section is devoted to the mechanical design of the system, Figure II-1 shows an electrical schematic. This is done here to define the names of the hardware parts that make up the physical plant. The main parts are:

1. High Voltage Capacitor (4 μ F, 15 kV)
2. High Voltage Power Supply
3. Ignitor Unit
4. Power Transfer System
5. Antenna Coil (Disk Coil)

Items 1 through 3 are self-contained units. In principle they are commercially available. However, in view of the goal that there should be a practical device following the present prototype, steps were taken that these three items can be acquired at a practical price tag. At present this is not the case for items 2 and 3. Therefore, these items were built in-house using inexpensive mass products. The details (parts list and circuit diagrams can be found in Appendix A).

The power transfer system (item 4) comprises the full wave rectifier, the power transfer bus bars, and the main spark gap. The power to be transferred from the capacitor is delivered via bus bars to the antenna coil (item 5) that radiates the generated electromagnetic pulse (EM pulse). Figure II-2 is a photograph of the bus bars prior to assembly into the 6" PVC pipe. Figure II-3 is a photograph of the main spark gap. The reason for the long distance between the capacitor and the antenna coil is to explore the possibility of staying an appreciable distance away from the fire. Eventually the bus bar will have to be replaced by a bundle of long coax cables.

The design of the spark gap is somewhat unusual. To deliver short pulses over relatively long distances, it is necessary to have forward current and return current in close proximity. The area between these two is proportional to the logarithm of the inductance to which these currents are exposed. Low inductance is important to achieve short rise times and, therefore, high power pulses.

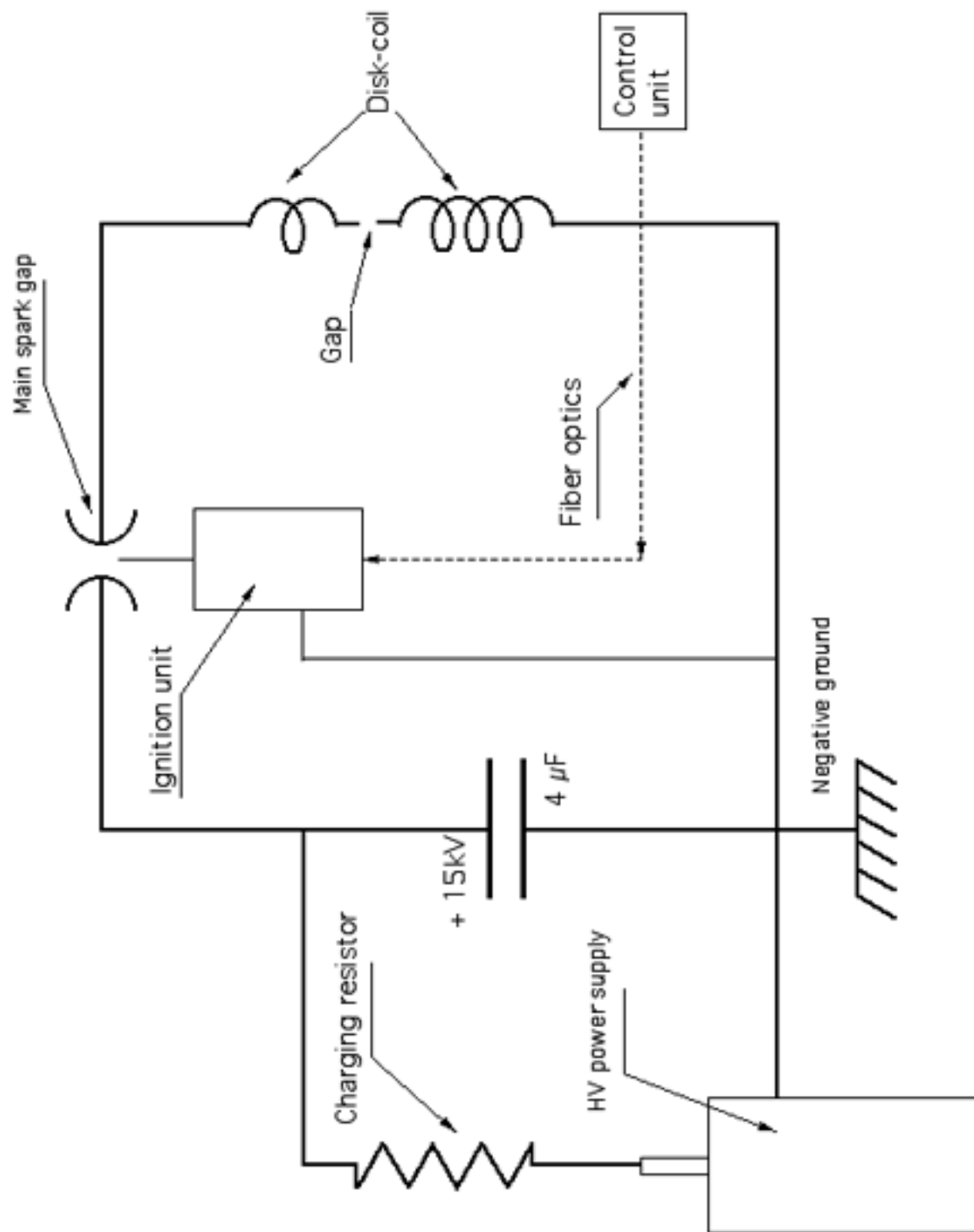


Figure II-1. Schematic Circuit Diagram of Device



Figure II-2. Bus Bars



Figure II-3. Main Spark Gap

Low inductance can be achieved either by a coaxial configuration or by a pair of flat conductors that are in close proximity. For the present effort the latter option was chosen. It is cheaper and sturdier than the coaxial option. A disadvantage is that a flat spark gap needs to be used, which has a larger inductance than a coaxial one. However, the operational results show that the spark gap as shown in Figure II-3 is a viable alternate to a coaxial spark gap. Aside from the fact that the flat spark gap is inexpensive compared to coaxial gaps that are available commercially, it also has advantages. Especially useful is the exposed position of the trigger wire (trigger pin). This not only allows for controlling the electrode to which the trigger spark will jump, but it also helps to achieve modifications in the static breakdown voltage just by adjusting the distance between the trigger pin and the electrode.

This is an important point if it is desired to reproduce this type of spark gap. Just the fact that this trigger pin is present (and is connected to ground via the secondary of a pulse transformer) modifies the static breakdown voltage. Therefore, adjusting the electrode distance for the desired static breakdown voltage without the trigger pin present will result in a much too narrow setting. Of course the longer the spark in the main spark gap is, the larger is the build-up time of the self-sustaining discharge that carries the large current. This means a longer pulse rise time. Nevertheless, 100 nanosecond rise times have been achieved with the flat spark gap. One should realize also that the flat spark gap operates in a different discharge mode than the coaxial spark gap. The flat spark gap is an atmospheric pressure glow discharge (albeit at high currents). The reason is that the size of the cathode spot is not restricted. The result is that the current density, for a given current, is considerably smaller than it is in a coaxial spark gap. Also the anode is not consumed; all that needs to be done is to re-polish the electrodes occasionally. These are easily accessible and do not require substantial disassembly of the device, as a coaxial spark gap would require.

Item 5, the antenna coil, is of novel design and is the most important component of the device. In view of its configuration it is in the following called the “disk coil”. Figure II-4 is a photograph of the disk coil; Figure II-5 is a drawing of the disk coil. The disk coil consist of a nylon body into which concentric circular grooves are machined. A continuous 12 gauge bare copper wire is fed into the grooves. The wire crosses over to the next groove in a channel provided for this purpose. The wire enters and leaves the coil body from the back side. Initially the wire is continuous but after a few shots the wire is cut manually

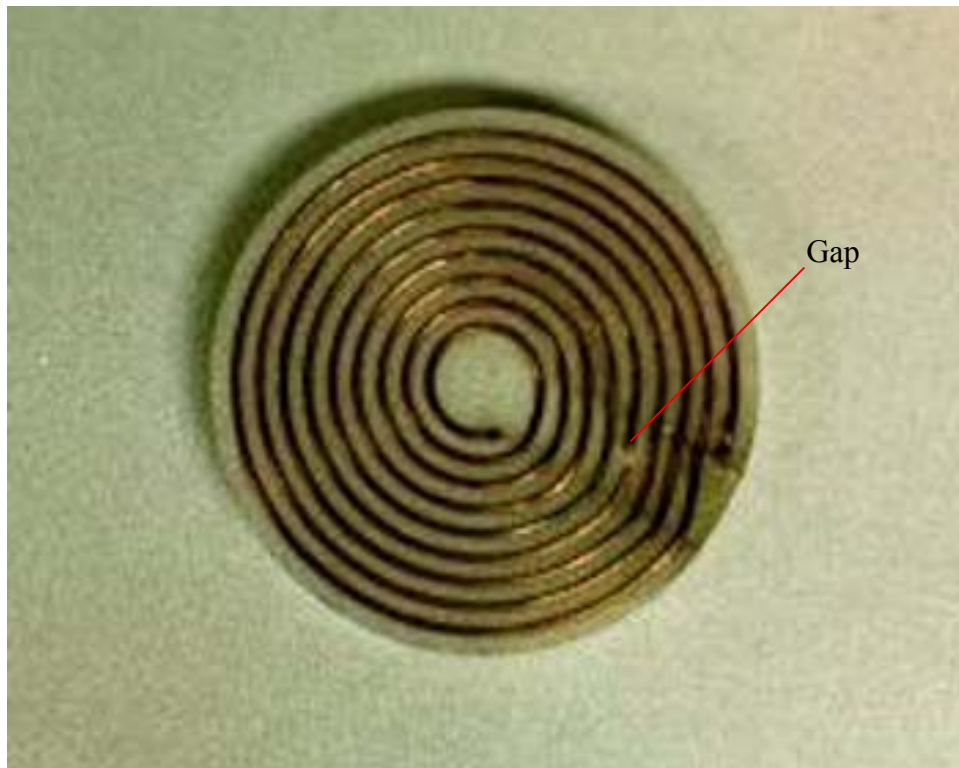


Figure II-4. Photograph of Disk Coil

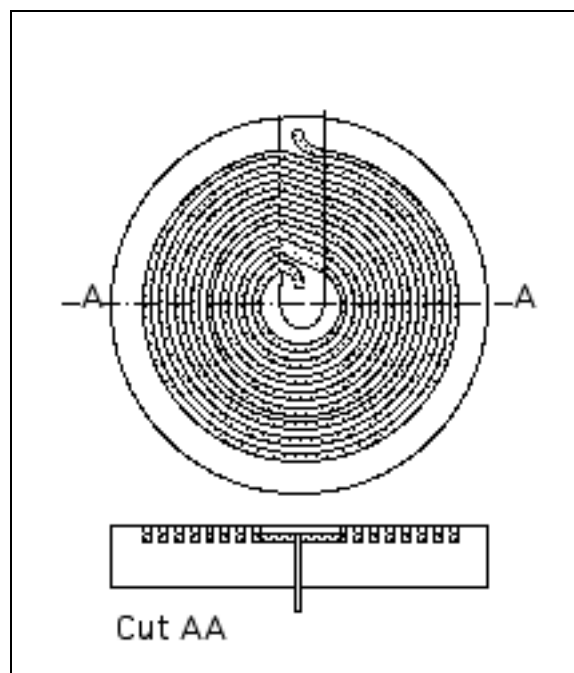


Figure II-5. Drawing of Disk Coil

at the third channel counting from the outer edge. The initial gap was in most cases less than 1 mm. Some coils underwent a large number of shots. During such extended operation the gap grew to up to 5 mm. The placement and number of turns is critical. Using the channel, it was easy to make changes. This configuration should be considered as a breadboard for coil development. Of course, for mass production, the channel is not necessary. The correct spiral can be cut which makes the feeding of the wire easier.

For the coil body various materials were tested. These were nylon, epoxy and machinable ceramics. The epoxy has the advantage that for mass production the coils can be poured. Ceramic coils can be inserted into the fire in case of special applications. Nylon delivered the best performance and was, therefore used for research purposes.

Figure II-6 is a drawing, of one unit showing the geometrical dimensions. Figure II-7 is a photograph showing the physical appearance of one of the 10 units built.

2. Electrical Design

The capacitor (4 μ F) is charged up to 15 kV by the high voltage power supply. The capacitor is connected via the main spark gap to a load. This load is the disk coil. The main spark gap is triggered by an ignition unit capable of about 30 kV. The trigger pin is flexible and can be located in various positions. This allows one to select to which of the two electrodes the trigger spark will jump. It turns out that the most reliable operation is achieved when the trigger spark jumps to the floating part of the circuit. The floating part is the section between the right electrode (see Figure II-1) of the main spark gap and the top half of the load which is the disk coil. Note that there is a gap in the windings of the disk coil.

It should be noted that it is possible to ground both electrodes of the main spark gap using a high voltage switch. If this is done there would be no danger in touching the disk electrode until the system is ready to fire. Access to the disk coil should be blocked by a suitable safety device based on whether the high voltage switch is open or closed.

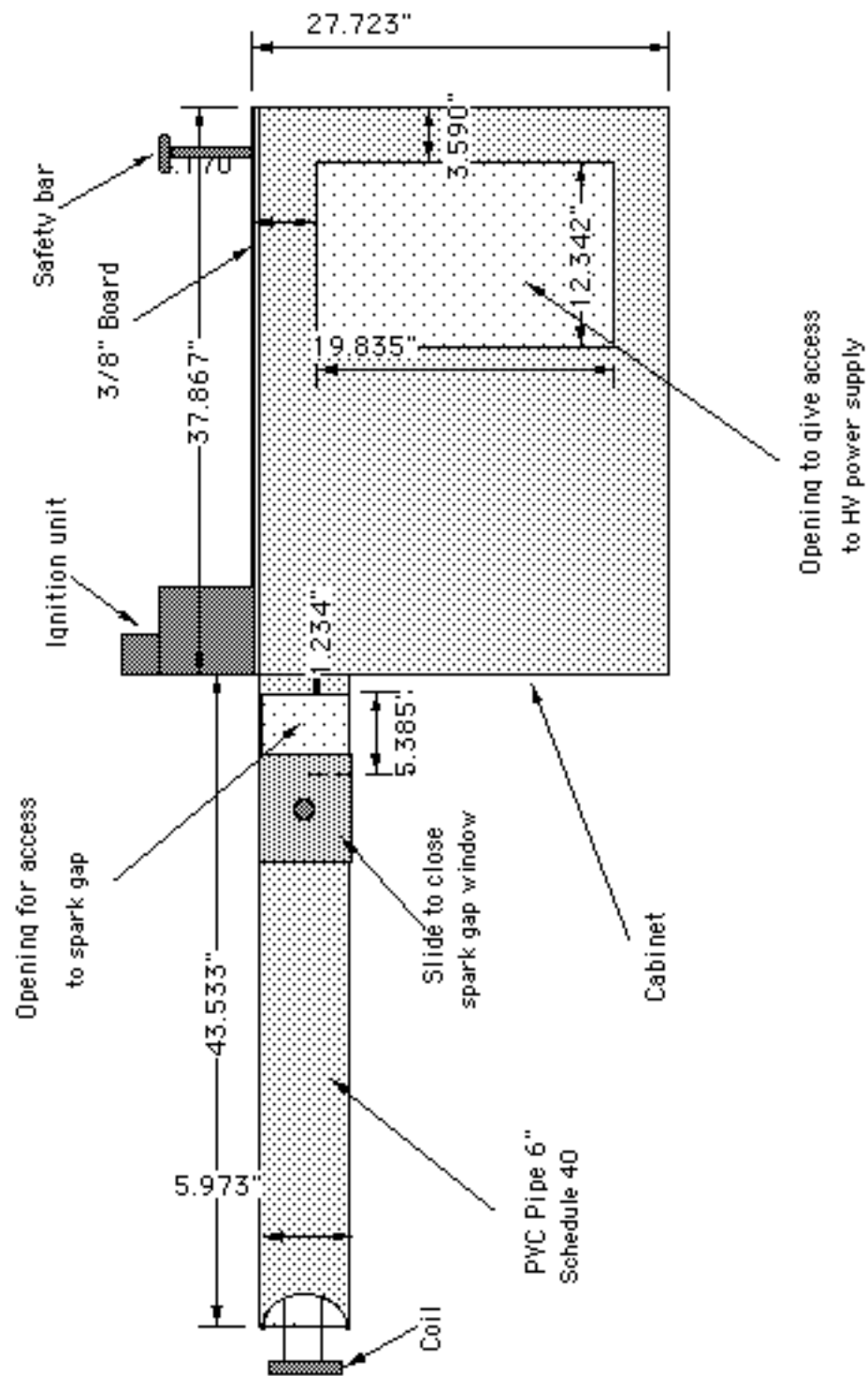


Figure II-6. Drawing of One Unit



Figure II-7. One Original Unit

During the Phase II effort no such switch was installed. Instead of this the disk coil was contained in a tube section and therefore inadvertent access to the coil was difficult but not impossible. However, considering that properly trained researchers were using the facility the danger was kept to a minimum. All high voltage research is dangerous and the personnel has to be trained for this type of work. There was no accident during the two years of operation.

For purposes of initial discussions, it will suffice to point out that the magnetic field created by the current flowing in the coil and the current itself flowing in the gap are more or less perpendicular to each other. Therefore, a $j \times B$ situation exists. This, of course, results in a force that acts on the plasma in the gap and throws it out of this gap. The consequence of this is a (rapid) interruption of the current.

One of the experiences gained with the pre-prototype was that a fast change in either the magnetic or electric field is required for flame extinguishment. Fast switching of high voltages is certainly a challenge. The goal is to achieve rise times (or fall times) on the order of tens of nanoseconds. For example, a Blumlein circuit does high voltage switching with two highly polished surfaces in close proximity using field emission as the switching mechanism. The present circuit is the magnetic analog.

Obviously the mass of the plasma in the gap of the disk coil is very small; and therefore, even a small force will be able to accelerate it strongly and so move it out of the gap. In "Section III. Operation of Device" it is shown that the rise time of the magnetic field is on the order of 100 nanoseconds. Small rise times of any field can mean that even small amounts of energy are delivered in the form of high powers. Common sense suggests that the amount of energy that is present in a flame can hardly be matched by an electromagnetic wave generated by a reasonably sized device. Therefore, from the beginning it was the intent to seek fast rise times.

The trigger spark that activates the main spark gap is generated by an ignition unit. It utilizes mostly existing mass products. Its circuit diagram can be found in "Appendix A." Although the units are intended for extinguishing ongoing fires, triggering is still required. The reason is that once a pool flame is extinguished, hot gases still linger above the flame and emit infrared (IR) radiation, which is capable of re-igniting the pool. Therefore the extinguishing shot has to be

followed up by one or more shots. These shots have to be triggered by a control unit in a preset time sequence. The circuit diagram of this control unit is also depicted in “Appendix A.”

The above description refers to one of the 10 units built. For extinguishment of the 8.5~ pan fire or the 24~ linear flame front, these units were lined up side by side and sequentially triggered.

Figure II-8 is a photograph of nine units assembled in a semicircle.

3. Test set-up

The test set-up comprises electrical measurements, optical measurements, photographic diagnostics and spectroscopy. Since the present effort is a development effort with the aim of demonstrating that fires can be extinguished by electromagnetic pulses (EM pulses), the diagnostics of the phenomenon is accordingly pragmatic. This means it was intended to find out how to maximize performance rather than exploring the extinguishment mechanism. To get involved in the latter would have been premature before it is demonstrated that the effect actually exists. Also considering the state of combustion research after 100 years, one could safely say that to explain the extinguishment mechanism would certainly take more than two years and would involve more than one research group.

a. Electrical Measurements: Obviously one would be interested in the relationships of voltage and current vs. time. Of special interest is the initial rise time of these quantities. Voltage can be measured across the terminals of the main capacitor. This was accomplished with a ohmic voltage divider probe (1:1000). The ratio of the resistors can be guaranteed to within 0.5% and the current flowing is not large enough to heat the resistors enough that this ratio will change to exceed this error. Such a probe was used during the charging process prior to firing. Therefore the voltage to which the capacitor was charged should be known to within the above error of measurement. However, such a probe will not be sufficiently fast to monitor the voltage fall time correctly once the discharge is initiated. There

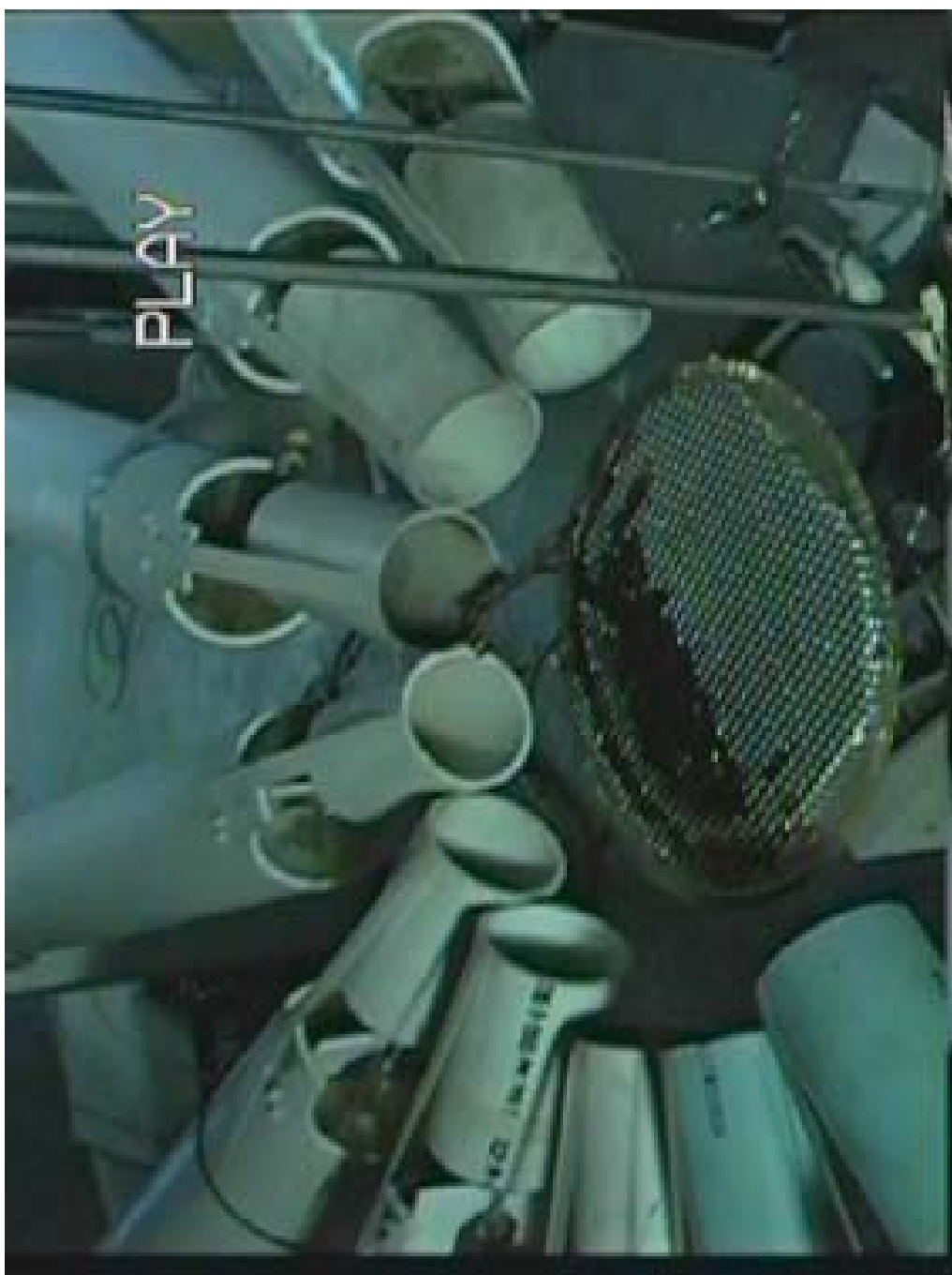


Figure II-8. Photograph of Nine Units

are HV probes for such a frequency range commercially available. For voltage measurements up to 15 kV the Tektronix P6013A probe and the Yokogawa HV15HF were used.

Measurement of current was initially performed using Rogowski coils of our own design. Those can be calibrated based on their geometrical dimensions and the number of turns from basic principles. Nevertheless, there are still calibration procedures published in the literature. We used a pulse generator at low currents to calibrate our coils. At the later stages of the effort the interest was more toward the relative change in time rather than the absolute value of the current. For this purpose a current sensor was developed. Figure II-9 is a drawing of the current sensor and Figure II-10 is a photograph of such a sensor.

Figure II-11 shows the instrumental set-up used for optical measurements, excluding spectroscopic measurements. (For spectroscopic measurements, see “Section IV. Other Observations”.)

b. Optical Measurements: The discharge that creates the EM pulse produces high intensity light pulses. To investigate the intensity vs. time two different detectors of our own design were used. One detector measured the UV (ultraviolet) region and the other detector measured the IR (infrared) region of the light pulse. The circuit diagram for both detectors can be found in “Appendix A.” The rise time of both detectors is better than 1 microsecond.

The spectrum itself was investigated with a spectrometer of our own design. This instrument can be used as a scanning spectrometer and as a spectrograph. It uses a 5 x 5 cm grating having 1200 grooves per mm. The spectrometer has a focal length of 50 cm. When used as a spectrograph, photographic registration was used. In this case a spectral resolution of about 0.5 Angstrom units (0.05 nm) was achieved. For time resolved measurements of one particular spectrum line a photomultiplier tube was used. Most of the time the sodium D line was traced vs. time. In this case the spectral resolution is only determined by the effective line width and is therefore considerably better.

The sodium D line tracing was used to determine the point in time when the flame was extinguished. Therefore the rise time of the photomultiplier amplifier combination is important. The rise time is better than 1 microsecond. For a basic

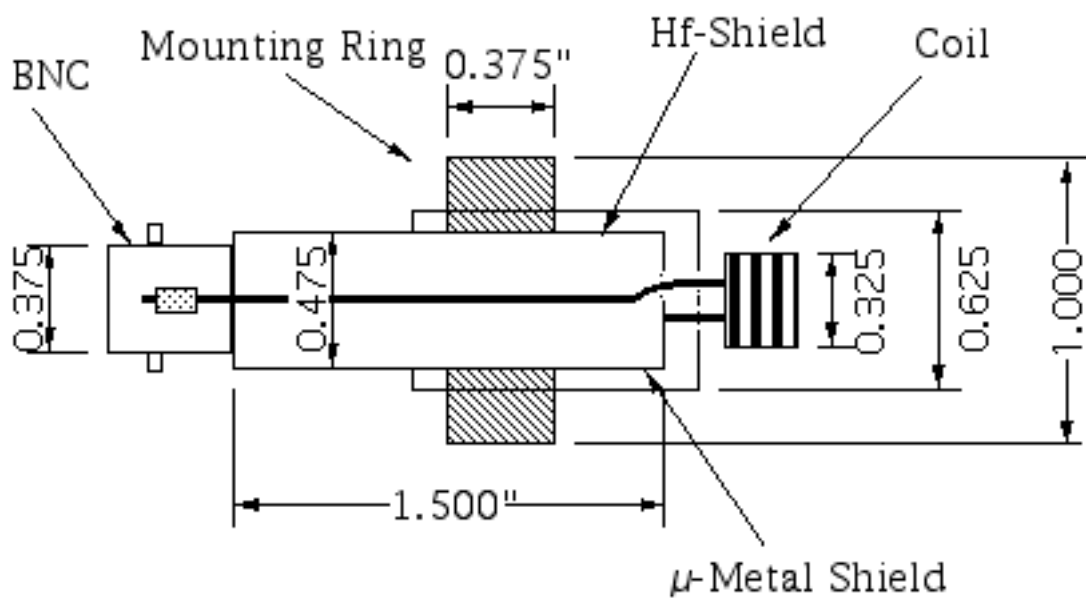


Figure II-9. Drawing of Current Sensor



Figure II-10. Current Sensor

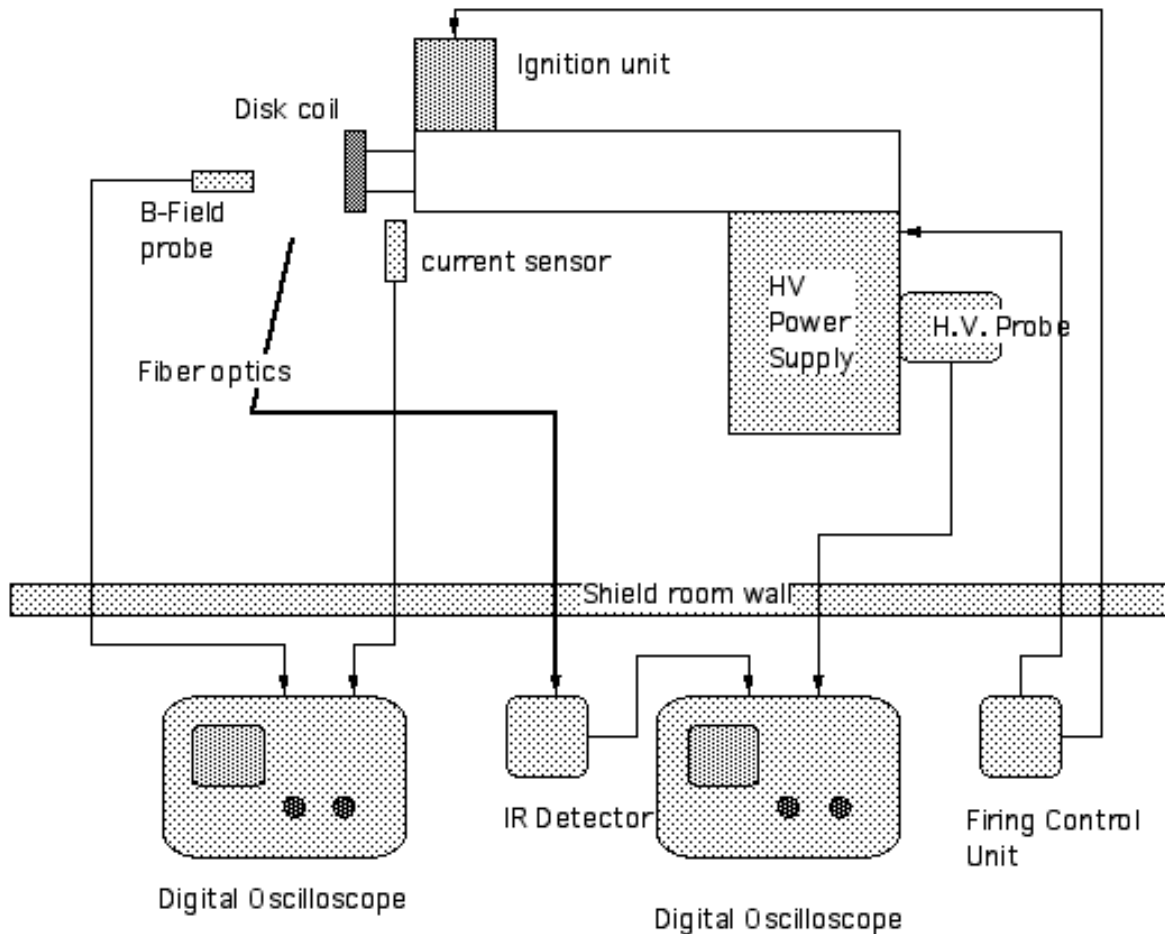


Figure II-11. Schematic of Instrumental Set-up

research effort one would have tried to measure the value of this rise time more exactly. However to explore the extinguishment time of an already ongoing fire a rise time of 1 microsecond is sufficient.

All measurements involving electronics were done using a room shielded for electromagnetic radiation. It had an outer skin of steel (sheet metal not screening) and an inner skin of aluminum foil. The measuring instruments were located inside the shield room, while the experiment was located outside the shield room. The electrical power was fed into the shield room via an isolation transformer. The

measuring signals were fed into the shield room with coaxial cable via coaxial feedthrough that were grounded to the outer steel skin of the shield room.

Other optical measurements involved video taping of the fire prior to and during the extinguishment. For this a High 8 camcorder was used. According to the National Television Standard one frame is about $1/30^{\text{th}}$ of a second. Since the discharge lasts only 20 microseconds one does not really expect very useful information from a video tape. However it turns out that the one frame that catches the discharge can be double exposed onto the image of the still burning fire. How this works is explained in the following section was the obtained video footage is discussed.

4. Operational Procedure

The operational procedure is as follow. The safety bar (see Figures II-6 and II-7) is removed from the position that shorts the capacitor and is inserted into the position that enables the power supply of each unit. This has to be done to each unit, if more than one unit (up to 10 units are possible) is to be operated. At this point in time all personnel shall leave the experimental area. The units are then operated from a shield room or any other room designated for this purpose. There must be interlocks installed that prevent personnel from reentering the experimental area until the shot has been fired and the capacitors have been shorted by a shorting relay. The latter one needs to be a high voltage switch that is available commercially. In addition, the floating parts of the disk coils need to be grounded by a grounding relay until charging of the capacitor commences. For research purposes, the shorting of the capacitor(s) was performed by inserting the safety bar by hand after the shot was fired. This procedure poses no hazard, since the voltage on the capacitor and on the coil is near zero at this time. The danger is that some personnel will enter the experimental area just prior to the shot to make last minute adjustments on the experiment. If these experiments described here are to be repeated at other laboratories, the local safety officer has to make provision in his own way to assure that no accident can happen.

A commercial unit that would be the second generation of the here described prototype needs to have these safety measure built in so that they automatically cut in. The disk coil should only be at high voltage a short time when the coil is placed close to the fire and the firing button is pushed. Upon the release of the firing

button the capacitors need to be automatically shorted. In a commercial unit there will no doubt be continuous firing at 60 Hz. This means that the capacitors have to be charged at this rate. In a real fire situation the power can be obtained from the primary side of the transformer that feeds the burning building. If the transformer is located on a pole, the wire that feeds the transformer can be attached to it with a hook located on a long insulated stick, as is sometime done in the utility industry. In this case there is no power supply nor a rectifying circuit needed. The main spark gap is set so that it fires before the peak voltage is reached. Therefore it will fire 120 times per second. As can be seen, the fire fighting device is now reduced to the disk coil and a capacitor. Probably the disk coil will be connected to the capacitor by a flexible coaxial cable.

Concerning the present prototype, if there is more than one unit to be operated, the firing sequence needs to be programmed into the central firing unit. The charging of the capacitors is then accomplished by enabling the power feed for the power supplies of those units to be operated. The yellow signal lights mounted on each unit will come on. The power supplies of each unit can be set to a certain maximum charging voltage. Once this voltage level has been achieved the red signal lights mounted on each unit will come on and further charging will cease automatically.

When the red signal lights on all units are illuminated, firing can be initiated by touching the firing button at the central control unit. (The circuit diagram of the control unit can be found in “Appendix A”). Before this is done it should be ascertained that all personnel are wearing hearing protection. The firing will produce a very loud bang (short sound wave) accompanied by a very bright light phenomenon. It is estimated that this light phenomenon is at least 100,000 times brighter than the flame.

5. Flame Configurations

The objective of the effort was to demonstrate that sizable heptane pool fires can be extinguished with an EM pulse without the use of additional chemicals, water or sand. Therefore, most of the work was done with heptane pool fires. In order to get some initial understanding of other uses of this technology propane flames of Bunsen burners and butane flames in mini torches were also extinguished. Most importantly burns of smokeless gun powder were performed

also. Here it was demonstrated that such an incipient burn can be detected and reacted to and extinguished in the early stages of the burn.

Heptane pool fires were investigated in two different forms. One configuration employed round pans and the other configuration consisted of a flame front. The pans used, had various diameters and were made of various materials, such as metals and ceramics. The largest pan used was 8.5~ in diameter. For formation of flame fronts a honeycomb structure was used. Figure II-12 is a photograph of the honeycomb structure. The cells are hexagons, made of aluminum having sides of 0.175~. The cells are 0.200~ deep and were usually filled with fuel up to their rim. If it was intended to form a flame front, only cells that were meant to participate in the flame front were filled with fuel; their neighbors were left empty. The cells are touching each other; therefore, when one cell is lighted it will ignite its neighbors and then this neighbor will ignite its neighbors, so that the whole flame front is started by one cell. In order to keep the aluminum walls of the cells from melting, the honeycomb sheet is partially imbedded in a poured solid structure of fiber reinforced epoxy. This will provide some cooling for a limited time only, but this arrangement has the advantage that the hot aluminum walls provides for strong flames that cover the entire flame front homogeneously, meaning this front does not bunch together like the flames in a open pan do.

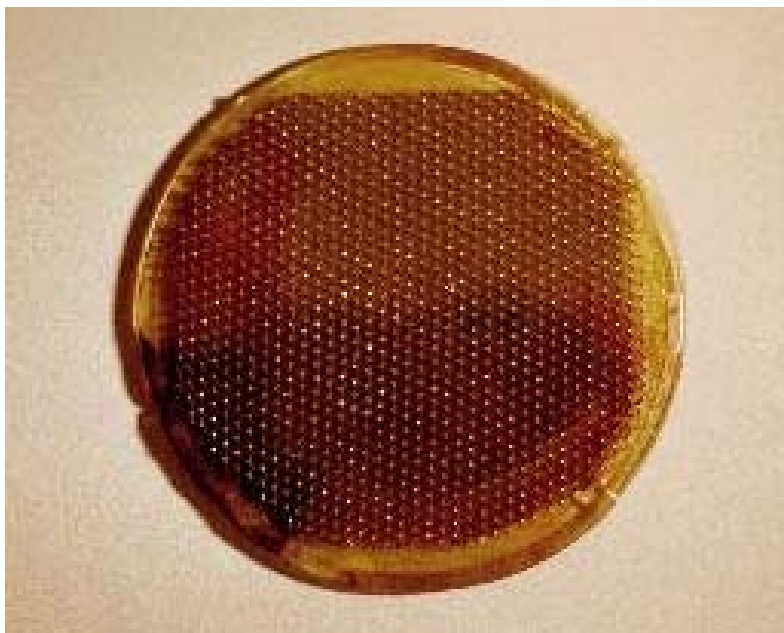


Figure II-12. Honeycomb Structure

Section III. Operation of Device

1. Introductory Remarks

Several flame types and sizes were investigated in the present effort. The basic goal was to extinguish a heptane pool fire and determine the maximum size that can be extinguished with the device developed under this effort.

The diameter of the pan of the largest heptane fire extinguished was 8.5" (21.59 cm). Also a flame front 24" wide and 2" deep was extinguished. In addition to heptane pan fires, forced flow flames were extinguished also. These were a Bunsen burner with a propane flame and a mini torch burning butane.

In this section the extinguishment of flame fronts is discussed first followed by a discussion of the large pan fire. The initial figures show the process with the room lights on. This is an exception. For proper sensor operation the room lights have to be off. The experiment is shown with the room lights on only to provide a view of the overall experimental set-up during operation. All later images in this report can be viewed with the experimental set-up in mind and so better understood.

2. Flame Extinguishment

a. Flame Fronts: Figure III-1 (a through L) show the extinguishment process of a flame front 24" long. Figure III-1 (a) shows the flame burning for some time prior to the first shot. In this particular experiment 9 units can be seen. They point to the round honeycomb array discussed in the previous section. Only cells that were supposed to form the flame front were filled with fuel (heptane). Neighboring cells were either filled with water or left empty. The water-filled cells act as a reflecting pool, which explains the mirror image seen in the figure. All cells filled with fuel are on fire.

Figure III-1 (b) shows the first shot. (In the following the discharge is called a "shot"). As can be seen the entire room is submerged in a blue light. This light stems from the plasma generated by the shot. In the figure only one unit was fired. The disk coils are located inside the smaller tubes that are placed in front of the larger tubes which are the prototype units. The reason for the smaller tube is to

shield the light that the plasma generates. The plasma is more or less confined inside these smaller tubes. Therefore the flames are not immersed in the plasma. Rough estimates obtained by photographic exposure tests suggests that light emitted from the plasma is a million times brighter than the light emitted by the flames. Without these shield tubes, photography would have been impossible. Figure III-1 (a through L) is obtained by a video camera (NTSC). The camera was running through the entire procedure. The figures shown here are individual frames of the obtained footage. This means the exposure time of one image is about $1/30^{\text{th}}$ of a second. The shot itself lasts about $40\ \mu\text{s}$. Therefore, there is a exposure reduction of about 1000. The plasma itself is not visible, since it is shielded by the smaller tubes. The blue light seen is reflection from the wall of the room. This fact can easily cause another 3 orders of magnitude in intensity reduction. Still Figure III-1 (b) is obviously a double exposure, since both the reflected plasma light and the flame emissions are both visible.

Normally it is not possible to double expose video frames. Fortunately the NTSC uses interlacing. This means each frame consists of two fields that constitute two complete images, albeit at a lower resolution (less lines) and a shorter exposure time (about $1/60^{\text{th}}$ of a second). The image represented by the second field is therefore taken at a later time than the image represented by the first field. The laws of probability see to it that once in a while it is possible that the shot (recognizable by blue light) is caught by one field and the flame alone is caught by the other field. Since the shot lasts only $40\ \mu\text{s}$ and the field lasts $1/60^{\text{th}}$ of a second it is feasible to do this although it may take a lot of work and patience. Sometimes it happens that the shot comes too late and the second field is already partially taken, for example in Figure III-1 (d). One may ask whether the plasma light, being so intense, would not overpower the detectors of the CCD device. The answer is that this actually might happen. However since the shot is so short only one line, or at most two lines would be wiped out. We have previous experience using CCD devices when gamma ray pulses were present for extreme short times. In these cases the one or two missing lines could be seen as noise. In the present experiment there seem to be no missing lines. This can be explained by the fact that the shielding is good enough to prevent this from happening.

The blue light in which the field is immersed is reflected plasma light from the wall and has no structure (image content). Therefore the lens distributes this more or less evenly over all detectors. The fact that this blue light persists over the

entire time that the second field is read out may be explained by either the blue sensitive detectors only are swamped or the air is fluorescing for that long.

The difference between Figure III-1 (a) and Figure III-1 (b) is minimal. The flame front became brighter and maybe somewhat more diffuse. Obviously nothing was extinguished, but the flame was slightly affected. The next shot is shown in Figure III-1 (c). There is no frame between the two shots. That means they were fired with an interval of about $1/30^{\text{th}}$ of a second. The second shot actually extinguished the flame front. What is visible are hot clouds hovering above the hexagon cells. These cells are actually visible, meaning the fuel is extinguished. (The fuel was not exhausted. This was checked by re-igniting the cells after the experiment was over). There is also another way to evaluate this. Flames do fluctuate, but they do this slowly. Within a $1/30^{\text{th}}$ of a second the shape of the flame should not change considerably. Compare Figure III-1 (a) and Figure III-1 (b). These two frames are $1/30^{\text{th}}$ of a second apart. The structure has not changed appreciably. Of course the intensity has changed, but such changes, if they are electronic interactions, can take place on the μs level. The shape of the clouds in Figure III-1 (c) is not related to the shape of the flames from which they were generated.

Figure III-1 (d) shows the next frame. There is no frame between Figure III-1 (c) and Figure III-1 (d). Again in the latter figure a shot is visible and a large part of the hot clouds has disappeared. Since this must have happened within $1/30^{\text{th}}$ of a second, the energy in these clouds could not have been dissipated by heat conduction. Radiation certainly must have played a role, as the increased intensity shows.

The next shot is shown in Figure III-1 (e). Again there is no frame between the consecutive figures. Whatever can be seen is a diffused hot fog having an even larger intensity. This shot obviously causes the cloud to get rid of its energy by radiation. The Figure III-1 (f) is also a consecutive frame. The shot did not fill the entire field. Considering that the interlacing goes backwards the shot must have happened when half of the field was already filled. The first field shows a beginning restart of the fuel. This restart has proceeded very fast since in the next consecutive frame, [III-1 (g)], a flame is already fully developed. However this is followed by another consecutive shot [III-1 (h)] that puts out the fire permanently. This is demonstrated by the next two consecutive shots [III-1 (i)] and [III-1 (j)]. Of course the two last shots were unnecessary; nevertheless they were followed by 2 additional shots [III-1 (k) & III-1 (L)]. Only the video revealed later that they were

unnecessary. Note that during the entire sequence each shot was only fired by one single unit. These units alternated in a sequence of about $1/30^{\text{th}}$ of a second.



Figure III-1 (a). Extinguishment Process of a Flame Front

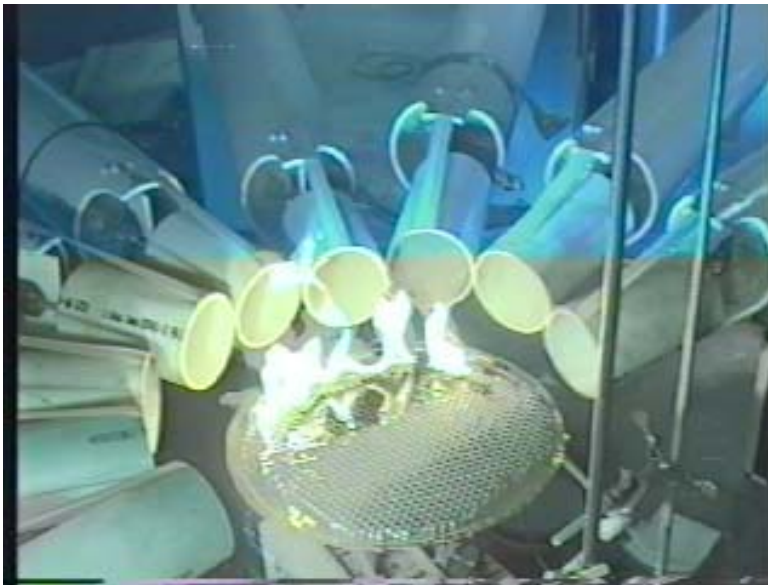


Figure III-1 (b). Extinguishment Process, continued

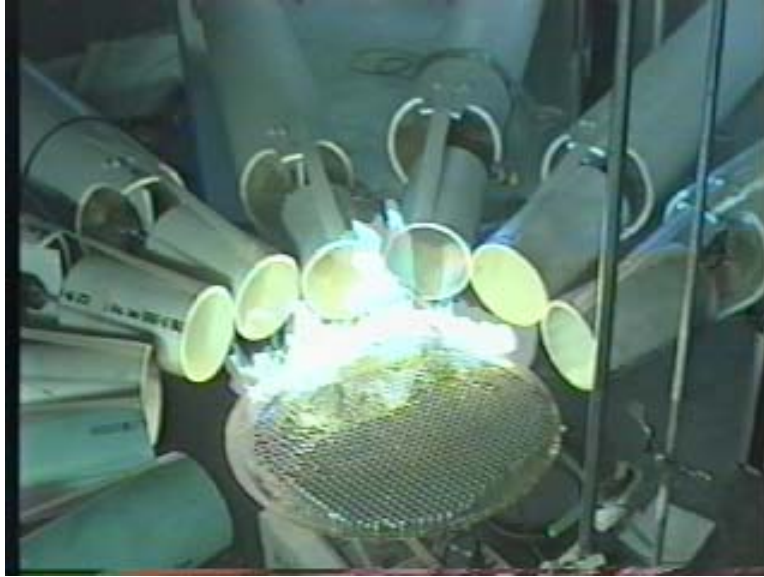


Figure III-1 (c). Extinguishment Process, continued

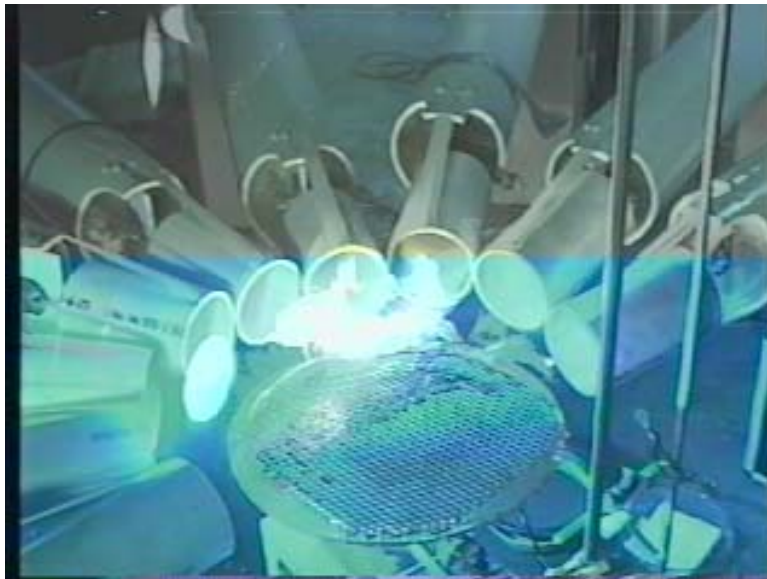


Figure III-1 (d). Extinguishment Process, continued

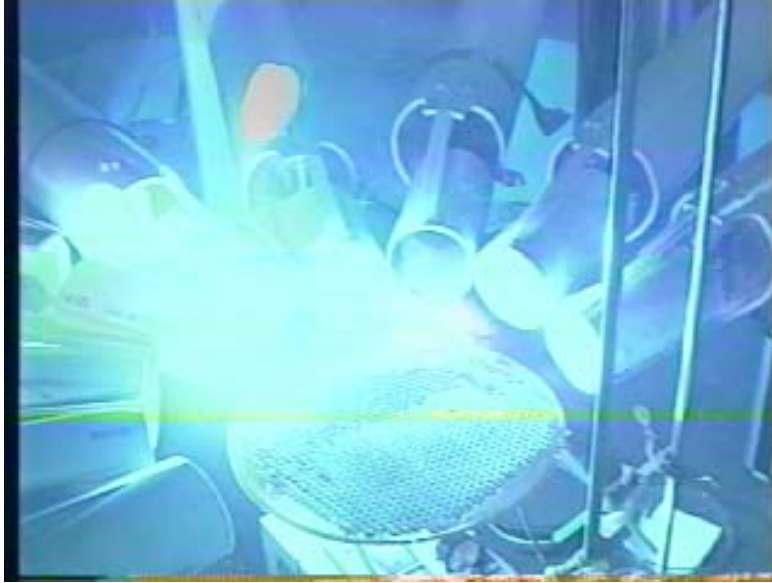


Figure III-1 (e). Extinguishment Process, continued

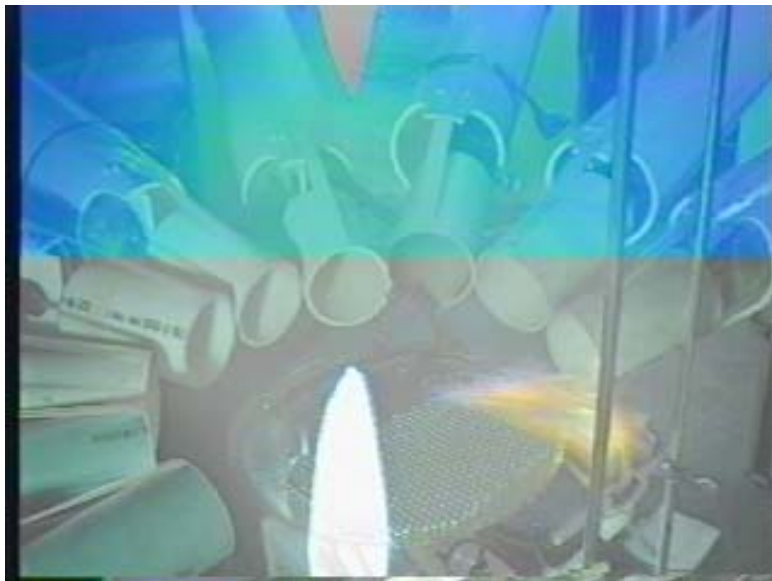


Figure III-1 (f). Extinguishment Process, continued

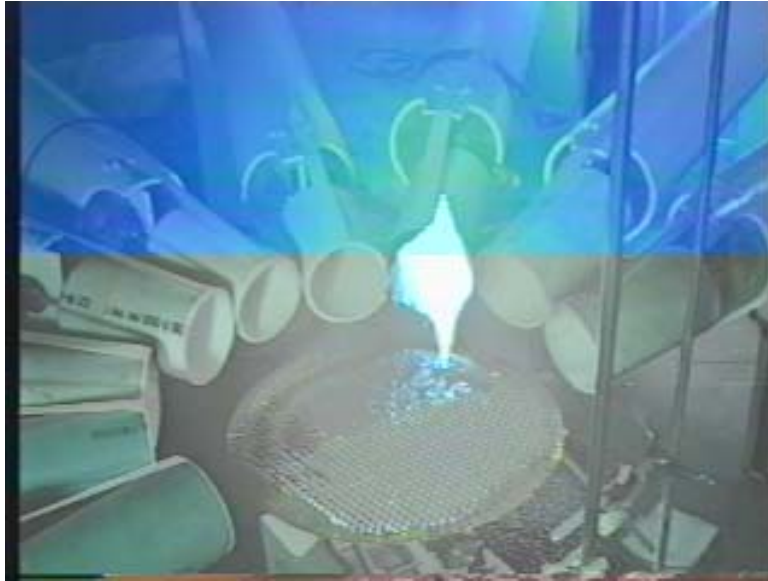


Figure III-1 (g). Extinguishment Process, continued



Figure III-1 (h). Extinguishment Process, continued

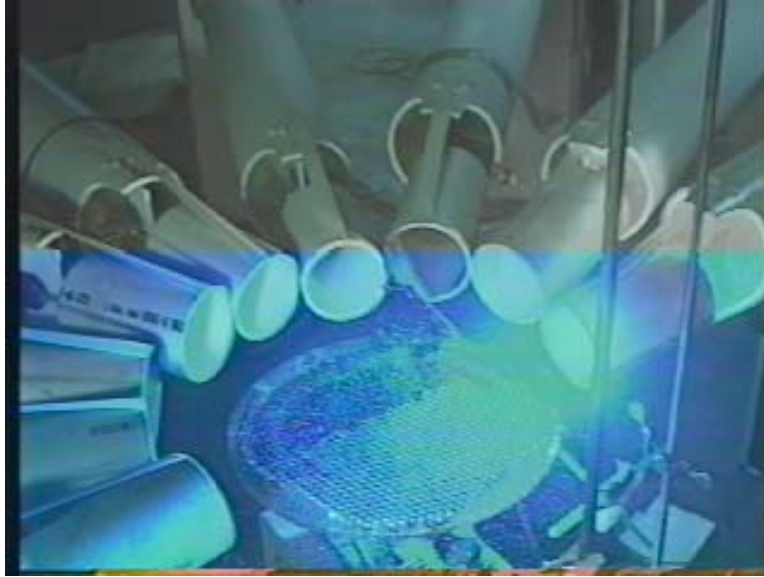


Figure III-1 (i). Extinguishment Process, continued

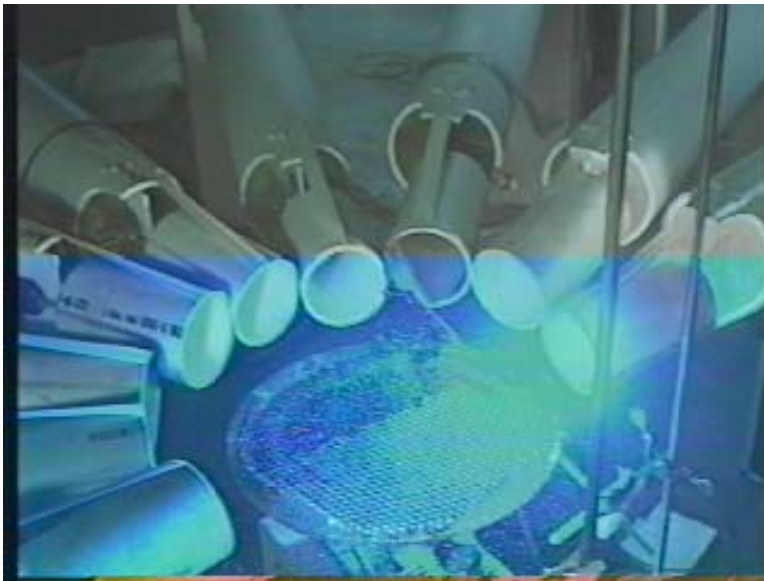


Figure III-1 (j). Extinguishment Process, continued



Figure III-1 (k). Extinguishment Process, continued



Figure III-1 (L). Extinguishment Process, end

The way the prototype is designed, the individual capacitors cannot be recharged in such a short time due to the limitation of the power supplies, although the capacitors could tolerate a recharging duty cycle of 100 Hz. If access to a grid of 15 kV, 60 Hz is available continuous operation is possible with the present prototype.

What can be learned from this sequence is that, in principle, one shot from one of the nine units is sufficient to extinguish the entire flame front, but not sufficient to extinguish that part of the flame body that is not connected to the fuel. Follow-up shots are required to rid this part of the flame body of its energy that normally is used to maintain the chain reaction and vaporize the liquid fuel. Undoubtedly a design for a commercial device should go to higher repetition rates, since the emission of the visible radiation seems to happen on the μ s level.

The question may arise whether the observed light is stimulated emission. In principle every populated electronic level can be stimulated. However, only if the stimulation light pulse is faster than the time required for spontaneous radiation and only if a population inversion exists, can a noticeable increase of the emission be expected. The light pulse provided by the plasma of the discharge has a rise time of about a microsecond. Therefore, for the present situation the observed increased emission must be explained by other phenomena. Also conclusions concerning the extinguishment process should not be drawn based on the observed video alone. For details see "Section VI. Extinguishment Mechanisms."

b. Pan Fires: An example of a firing sequence exposing a 8" heptane pan fire is given in the following Figures III-2 (a through L). Again these are individual frames of a video footage. (Only selected frames that are typical are shown.)

Figures III-2 (a) and III-2 (b) are showing the flame prior to the shot. Figure III-2 (c) shows the flame and the shot superimposed. In Figure III-2 (c) the flame was imaged into the first field before the shot was fired. Then the shot happened and it was imaged during acquisition of the second field.

The blue disks in the figure are the openings that contain the disk coils. Only one was fired, the others are illuminated by reflected light. The gun that fired the shot is to the very left in the image and not visible.

The next frame, Figure III-2 (d), shows the shot immediately after the double exposed frame. Here it can be seen that the fire is extinguished, but luminous hot clouds are hanging over the pan that is still full of fuel. (Again after a test was completed, it was always verified that there was still fuel left in the pan by re-igniting it by hand).

In the figure it can also be seen that the flame intensity is now brighter than it was before the shot. In the following frame(s), Figure III-2 (e) and III-2 (f), the luminous cloud becomes even brighter and drifts away from the pan so that the fact that there is no fire in the pan is clearly visible. The second shot is now fired and Figure III-2 (g) is again a double exposure. Since the fire is already out, the shot did not accomplish anything. In the next few frames, only one is shown in Figure III-2 (h), the brightness of the cloud recovers, probably feeding on unburned fuel vapor that is still around.

This is the beginning of a re-ignition. Figure III-2 (i) shows the progress of this re-ignition, still feeding on unburned fuel vapor. However, before it can touch down and re-ignite the liquid fuel the next shot happens, Figure III-2 (j). Now this structure is almost wiped out. There is still another shot that was actually unnecessary; the cloud is now too faint to cause re-ignition as Figure III-2 (k) demonstrates. Nevertheless, another shot was fired; the result is depicted in Figure III-2 (L) which demonstrates that it was unnecessary.

This, of course, is not foreseeable since the firing order is programmed into the master control unit prior to each sequence of firings. Typically the shots are separated by 100 milliseconds. Five shots were fired consecutively, while the camera runs uninterrupted. Afterwards those frames that were typical to demonstrate the flow of events were picked out by using software.

3. Structure of the Discharge

It should be pointed out that cutting the gap in the disk coil causes a substantial change in the structure of the discharge. A continuous disk coil (one that has no gap) will neither produce the light phenomenon, nor the sound wave and, above all, will not extinguish any fire. Therefore, as far as the present effort goes, putting a gap into the disk coil constitutes an innovation. The design of the disk coil itself is also an innovation.



Figure III-2 (a). Extinguishment Sequence of an 8" Pan Fire



Figure III-2 (b). Extinguishment Sequence, continued



Figure III-2 (c). Extinguishment Sequence, continued



Figure III-2 (d). Extinguishment Sequence, continued



Figure III-2 (e). Extinguishment Sequence, continued



Figure III-2 (f). Extinguishment Sequence, continued



Figure III-2 (g). Extinguishment Sequence, continued

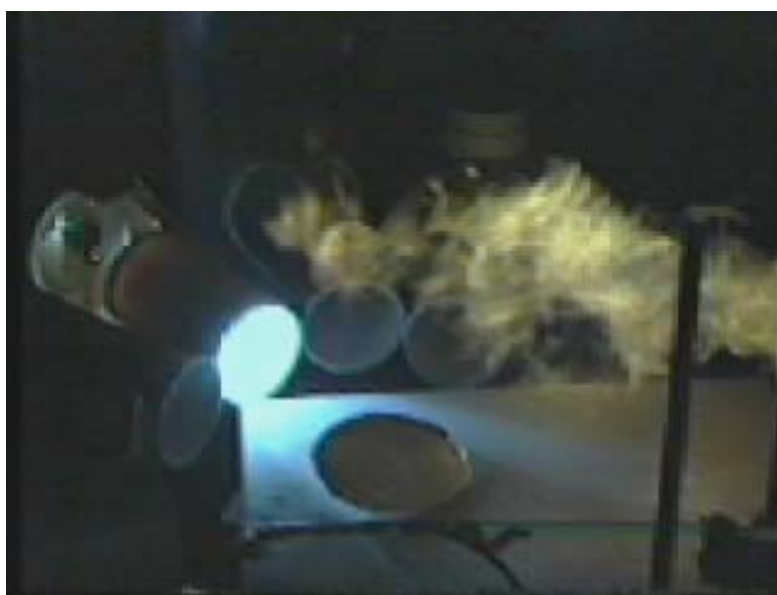


Figure III-2 (h). Extinguishment Sequence, continued



Figure III-2 (i). Extinguishment Sequence, continued



Figure III-2 (j). Extinguishment Sequence, continued



Figure III-2 (k). Extinguishment Sequence, continued



Figure III-2 (L). Extinguishment Sequence, end

In order to understand the reason for this change in the structure of the discharge, inductivity and resistivity of the circuit should be known. Since these values change quickly during the discharge, direct measurements are difficult. Therefore the following describes an attempt to derive these values by modeling the discharge.

As can be seen from Figure II-5 the disk coil is a solenoid coil that has nine “layers” but each layer is only one wire diameter long (in the axial direction). Ordinarily the reason for using solenoid coils is to get a large magnetic field with a relatively small current. However, the length of the solenoid coil contributes to the inductivity and so slows the current pulse down. For the creation of a continuous or slowly changing large magnetic field a regular solenoid coil can be used. In this case the current is used, so to speak, more than once to create a magnetic field. However a long magnetic field, as exists in the interior of a solenoid coil, is not required for the present application, since the fire necessarily needs to be outside the coil. Therefore, a large, short time magnetic pulse is required outside the coil. Consequently, multiple wire windings, as in a solenoid coil, are of no help. Large EM amplitudes and short rise times together can only be obtained by a large pulsed current. This challenge is met by the design of the disk coil. In such a design, more windings in the only layer might help somewhat. However, there is a requirement to keep a minimum distance between the individual windings to prevent the high voltage from jumping between them. More windings would therefore require more area, which would degrade density of the magnetic field intensity.

In the following the difference caused by cutting a gap in a disk coil will be demonstrated. In Figure III-3 oscilloscope traces are shown that are obtained with a disk coil without a gap (“un-cut coil”). It shows voltage and current of this disk coil. The voltage is measured at the terminals of the capacitor using a Tektronix high voltage probe. The current is measured with the current sensor described in the previous section. This sensor is placed in front of the disk coil at a distance of 25 cm. The behavior of the circuit is as can be expected from a harmonic oscillator based on its inductance and capacitance. However, there is one exception, namely the initial onset of the current is much faster than can be expected from an already vibrating oscillator. What happens here can be compared to a mechanical pendulum, (for example a weight on a string) that is started by a blow with a hammer. The initial swing will be erratic and faster than the eventual harmonic frequency of the pendulum. In this case the initial settling time also will be less than the first half of the first full period.

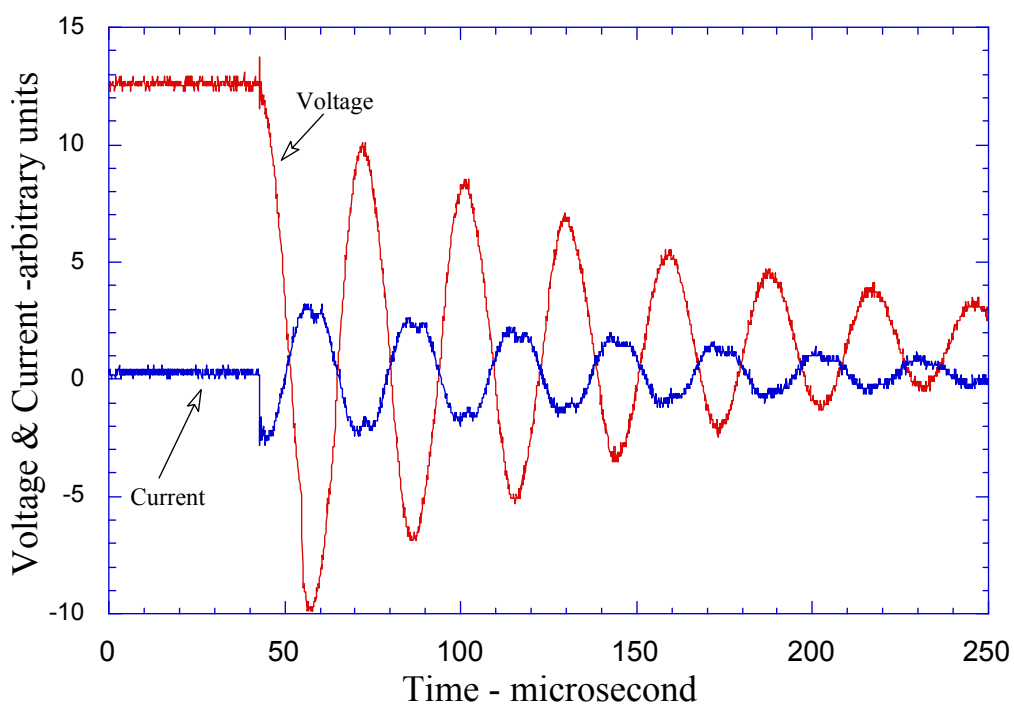


Figure III-3. Voltage and Current of a Un-cut Coil

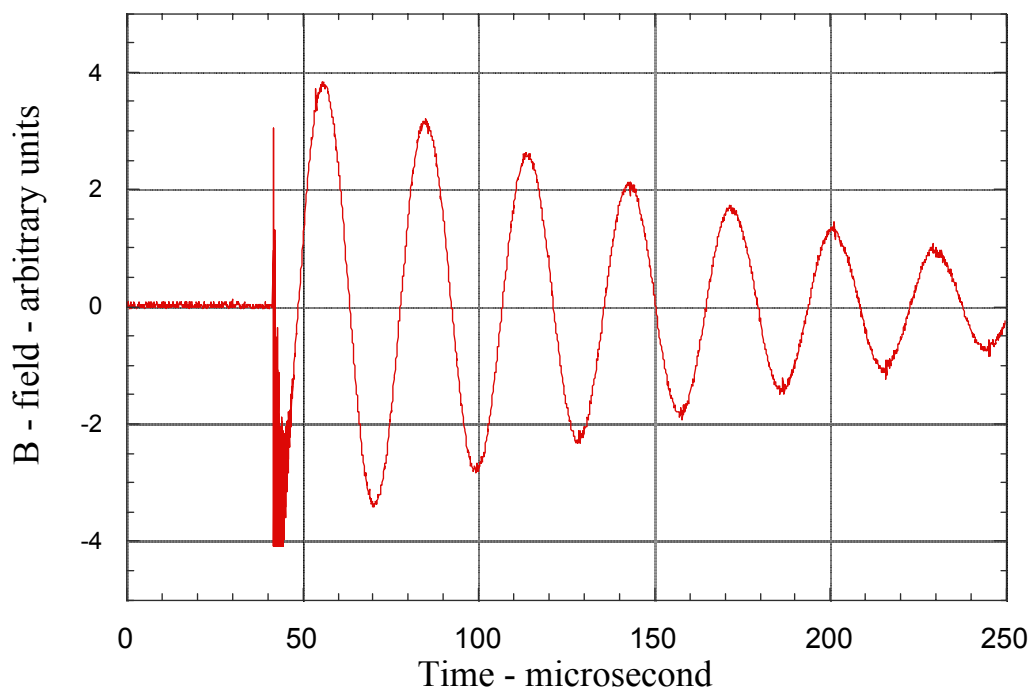


Figure III-4. B-Field of a Un-cut Coil

Figure III-4 shows the B-field of the “un-cut” coil. As can be seen, the first half of the first period is erratic. Figure III-5 shows the first 10 microseconds in detail. (The apparent saturation is caused by the oscilloscope. The figure is a replot of the digital data provided by the digital oscilloscope. The lower edge of the oscilloscope window was at -4 arbitrary units). The figure shows that there are at least two different waves superimposed. This leads to the conclusion that during the first period a high frequency wave is superimposed to the base wave. The superimposed frequency is typically 2.5 MHz while the base frequency is only 34.7 kHz. The initial four periods of the superimposed high frequencies go above the zero line, the rest do not. Therefore, it should be concluded that this phenomenon is a vibration in the plasma and is not controlled by the inductance and capacitance of the circuit as the base wave is.

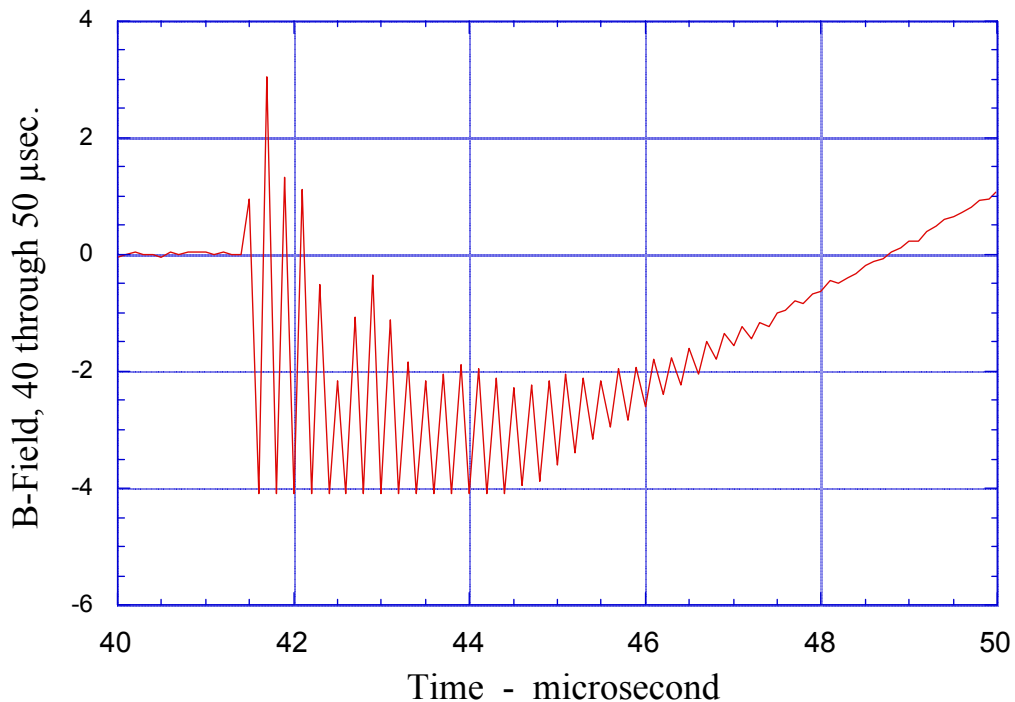


Figure III-5. B-Field detail, 40 through 50 μ s.

That plasmas in arcs or sparks can vibrate at high frequencies is nothing new. As a matter of fact, the first radio transmissions were made this way. What is different here is that the base frequency seen in Figures III-3 and III-4 is determined by the inductivity and capacity inherent in the circuit. The super-

imposed higher frequency is the start-up phase (the blow with the hammer) and must be created by decaying of alternate electric and magnetic fields. Since the disk coil has no cut, this must be happening in the main spark gap.

Next the situation will be shown that exists if the disk coil is cut, as described previously. Figure III-6 shows voltage and current after creating the gap and Figure III-7 shows the B-field and the accompanying IR radiation. For a better comparison Figure III-6 (coil with cut) and Figure III-3 (coil without cut) are reproduced with the same time scale in Figure III-8. As can be seen the changes that occur due to the fact that there is a gap in the disk coil are significant. The base frequency is now 77 kHz, which is an increase by a factor of 2.2. Also the damping has increased significantly. Damping is caused by energy losses. These are mostly ohmic losses, but radiation losses also become important at higher frequencies. The ohmic losses caused by the circuitry can be deduced from the logarithmic decay of the waves in Figures III-3 and III-6. At least a part of the additional damping seen in Figure III-6 must be caused by radiation losses. One could argue that the main spark gap will also change its ohmic resistance due to the fact that there is now a larger current flowing. However, due to the negative VI characteristic (voltage vs. current) of an arc discharge, the ohmic resistance should decrease rather than increase. Only if the current is large enough that the operating point is past the minimum of the VI characteristic, will the ohmic resistance increase with increasing current (which may very well be the case here).

In addition radiation losses should certainly exist. There is high intensity optical radiation, rf (radio frequency) radiation and even acoustical radiation. Since the flame is some distance away (it is not immersed in the plasma) any influence on the flame (including extinguishment) has to come in the form of radiation (light and rf) and to a lesser degree from mechanical influences (sound, air puff, etc.).

Therefore the changes between Figure III-3 (un-cut coil) and Figure III-6 (cut coil) point out that flame extinguishment is achieved by radiation, since the un-cut disk coil (Figure III-3) does not extinguish the flame and does not radiate light, while the cut disk coil (Figure III-6) does.

In the present effort, the current was initially measured with Rogowski coils. Here the quantity $-di/dt$ is picked up by a torus coil and its amplitude is integrated by an electronic circuit to obtain the current. The time constant of the integrating circuit is long compared the period of the current to be observed.

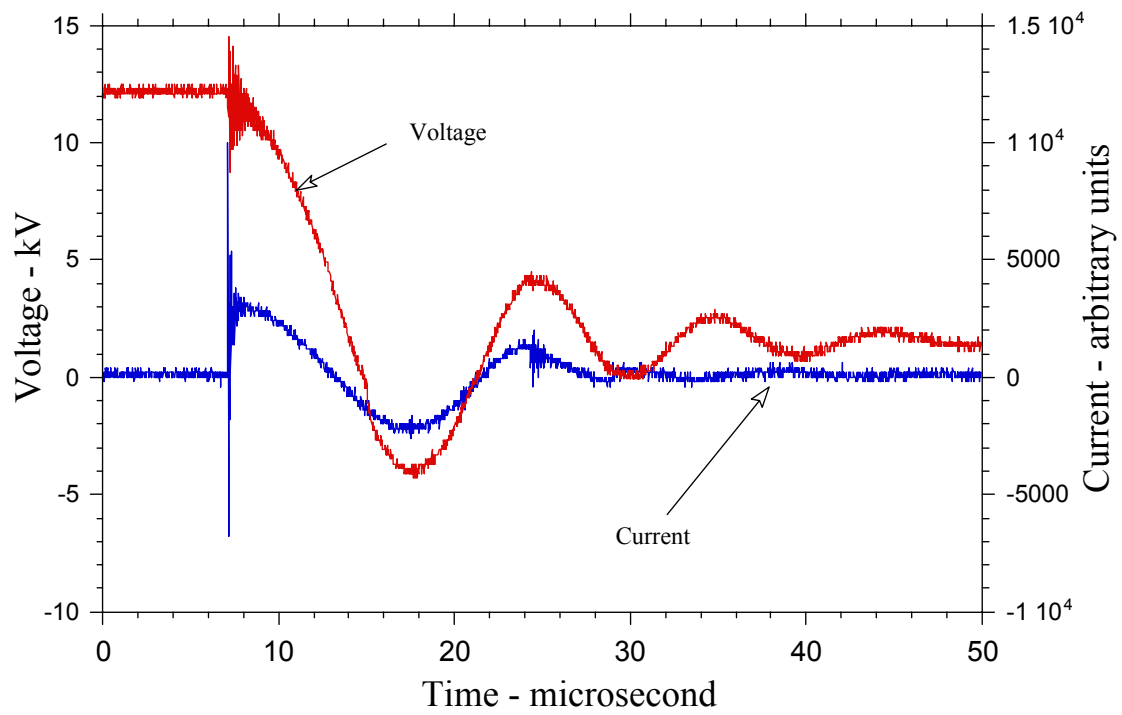


Figure III-6. Voltage & Current vs. Time for Cut Coil

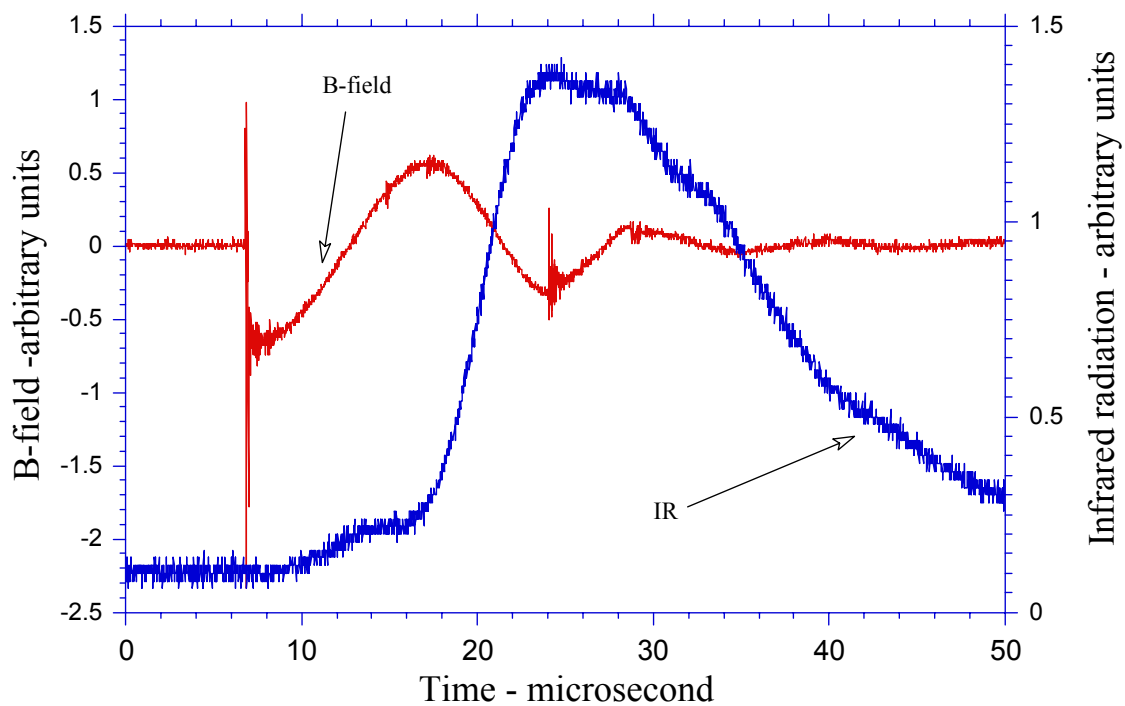


Figure III-7. B-Field & IR of Cut Coil

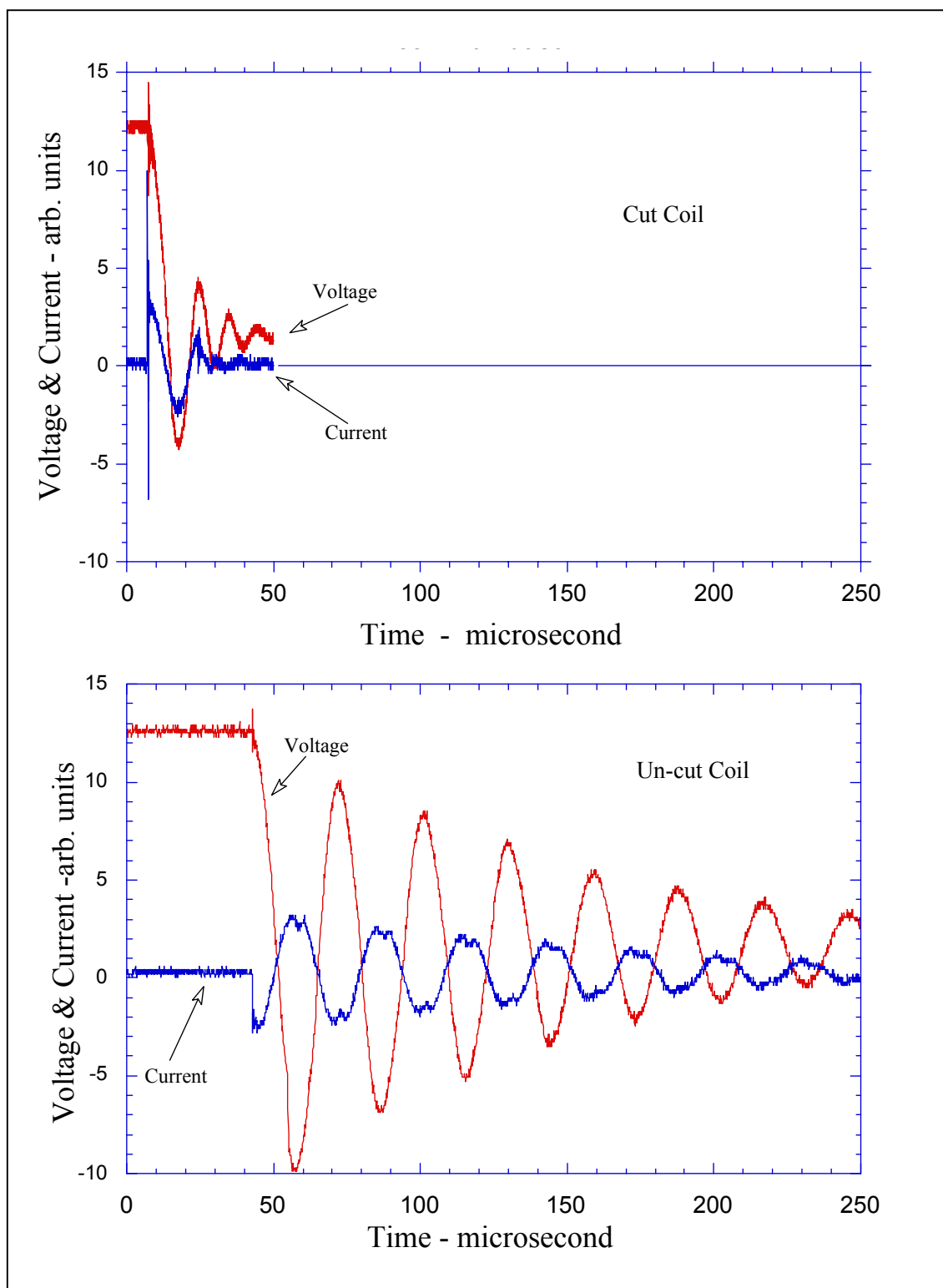


Figure III-8. Cut and Un-cut Coil Computed

In principle the sensitivity of a Rogowski coil can be computed from its geometric dimensions using first principles. Although Rogowski coils have been around since the early twentieth century, one still can find in the contemporary literature experimental calibration procedures for Rogowski coils.

It turns out that, for our purposes, the long time constant of the integrating circuit is detrimental, since the most important events happen in the first quarter of the first period. Therefore, we replaced the Rogowski coil with a current sensor of our own design. Such a current sensor comprises a small (1.0 cm diameter) solenoid coil of 5 turns. The solenoid axis is perpendicular to the straight wire that leads into the disk coil. Therefore it is a short section of a Rogowski coil without an integrating circuit. The coaxial cable leading to the oscilloscope is terminated with 50 ohms.

Since it is easier to measure time than the inductance and ohmic resistance of the circuit, it was decided to trace the magnetic field in front of the disk coil and find a theoretical curve that coincides with the observed magnetic field trace. The magnetic probe used for detection of the field was described in the previous section. The amplitude of the trace is arbitrary, but the logarithmic decrement is meaningful (since it is dimensionless).

The logarithm of the peak amplitudes of two consecutive periods is commonly called logarithmic decrement:

$$\delta = \ln(I_2/I_1)$$

I₁: the first current peak,
I₂: the second current peak

for the harmonic oscillator the log decrement δ is known to be:

$$\delta = (R/2L)T$$

R: ohmic resistance
L: inductance
T: current period

The current period, T, is easy to determine; therefore, R and L can so be determined as well. Since there are two independent variables L needs to be determined independently by using the equation:

$$T = 2\pi\sqrt{LC} \quad C: \text{capacity of the main capacitor.}$$

It is reasonable to assume that the capacity of the main capacitor will not change. Therefore, an initial value of T can be determined. This works well for the un-cut disk coil. For the cut coil there might be other capacities involved (stray capacities) that are significant enough to contribute to the change of frequency that is observed for the cut disk coil.

After R, L and C are determined the current itself can be determined by the equation:

$$I_0 = U\sqrt{C/L} \quad I_0: \text{maximum value of the current}$$

U: initial voltage on the capacitor

The so-determined values allow computation of the entire trace using the equation:

$$I(t) = I_0 e^{-\delta t} \sin(2\pi t/T) \quad t: \text{time}$$

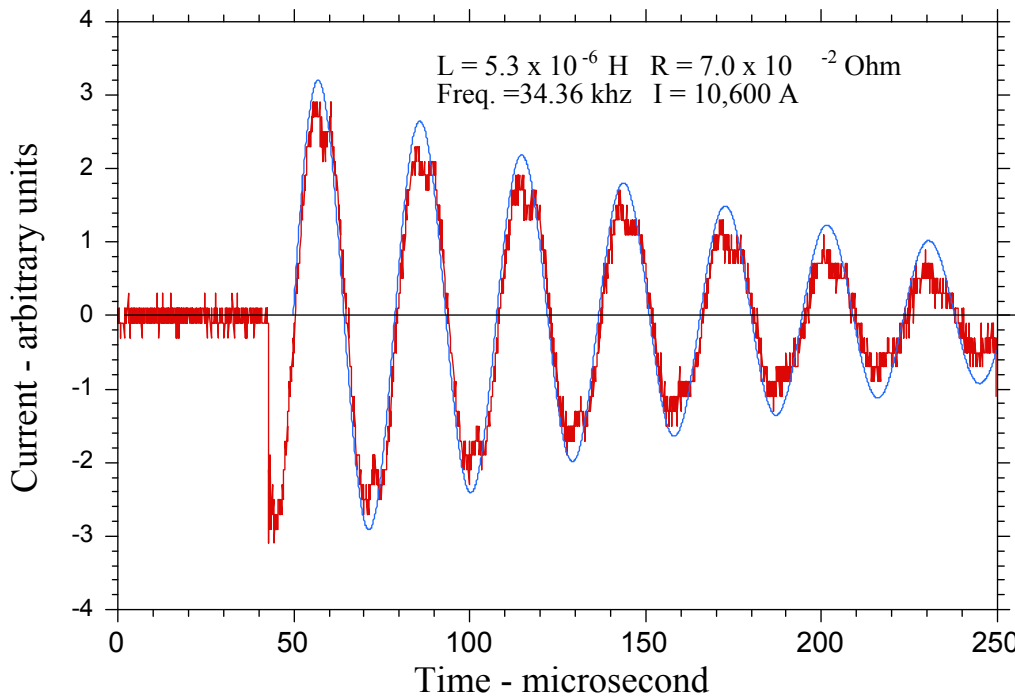


Figure III-9. Un-cut Coil, Experimental Data & Computed Values

This has been done for the un-cut coil, the result is shown in Figure III-9. As can be seen, the values given in the figure legend produce a theoretical trace that

fits the experimental trace well. (Note: whether the trace starts negative or positive is arbitrary. It depends on the direction of the winding of the magnetic probe.) The important point to make concerning the figure is that the first current peak seems to be cut in half. Of course a current in such a circuit has to be equal to zero at time zero. Therefore this trace suggests that a current does not seem to flow for about 1/4 period and then starts with a rise time (200 nanoseconds) that represent a tiny fraction of the following (constant) periods.

A possible explanation might be that the current indeed starts at zero at time $t = 0$. However, the amplitude of the continuous flowing current, which is the non-self containing discharge, is minuscule. This current will not be picked up by the current sensor. Upon initiation of the trigger spark, the discharge in the main spark gap will have to grow exponentially. This build up (rise time) is not controlled by the inherent resistance or inductance of the circuit. However, the maximum current value that can be reached is controlled by these two quantities (R and L). Figure III-10, which is a detail of Figure III-3, has a short time interval showing the exponential build-up. The data were taken by a digital Oscilloscope (Tektronix TDS 220). Therefore, the current rise time shown in the small detail contains only a few data points. The data points are spaced by 100 nanoseconds. The rise shown in Figure III-10 is defined by only 3 points:

$$\mu\text{s}\# 42.7 = -0.1; \quad \mu\text{s}\# 42.8 = -2.1; \quad \mu\text{s}\# 42.9 = -3.1$$

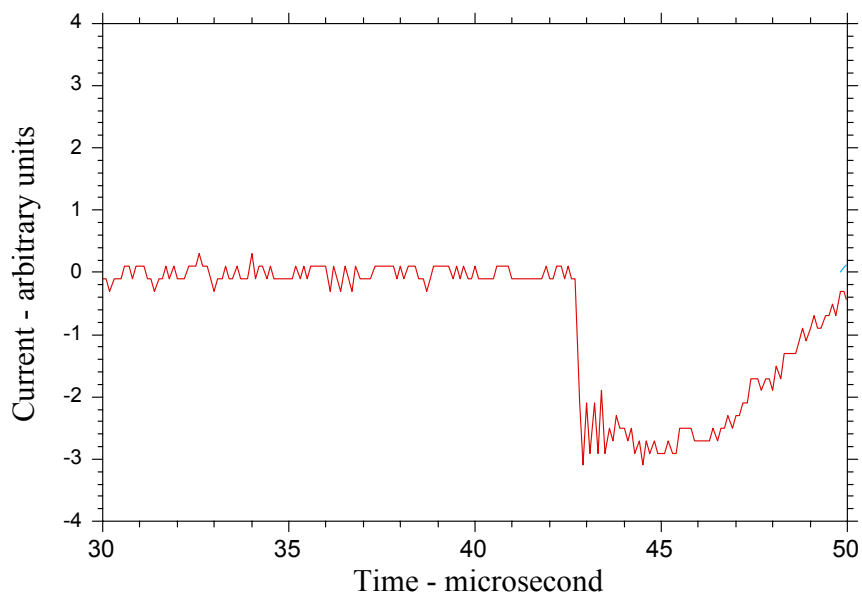


Figure III-10. Detail of Figure III-9 Un-cut Coil

The next data point is already past the peak, back up to $\mu\text{s}\# 43.0 = -2.20$. Therefore it is reasonable to say that the rise time was 200 nanoseconds, but whether it was indeed an exponential rise cannot be proved from this information. If one had doubts that the rise is exponential, one would have to study this rise separately using a closer data point spacing.

The more interesting feature is the metamorphosis that takes place when the coil is cut, causing the base frequency to increase by a factor of 2.2 and modifying the damping significantly. Figure III-11 shows the measured data and the computed values superimposed. The computed values are based on the ohmic resistance and inductance annotated in the figure. As can be seen there is a base frequency of 59.3 kHz that does not change over the life of the vibration. To conform to the computed base frequency, obviously at least one of the two spark gaps must be extinguished to cause the current to be zero during the first period of the vibration. The first quarter of the first period is missing and is substituted with an exponential rise similar to the un-cut coil. The same explanation as given for the un-cut coil seems to apply here as well.

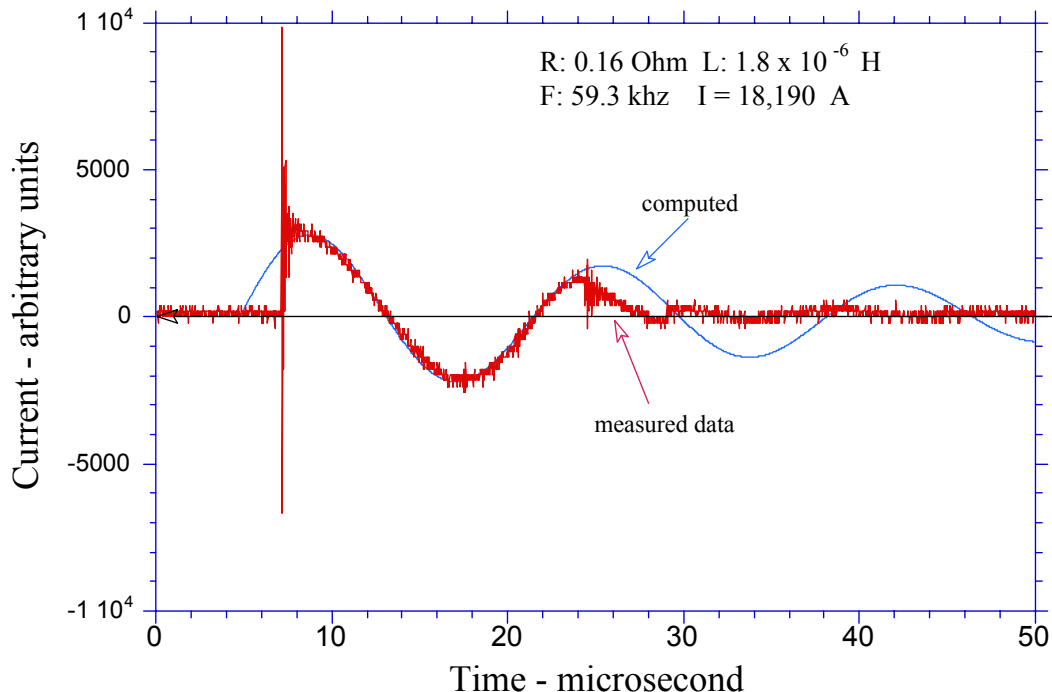


Figure III-11. Measured & Computed Data Superimposed

At the first quarter of the second period a breakdown that destroys part of the second quarter of the second period takes place. From here on the computed wave and the measured wave seem to be out of synch. However, at the end of the first half of the second period, there is again a exponential rise, albeit very small. The experience gained at the beginning of the measured wave suggests that at this point a quarter of the next period is skipped because this quarter is missing due to the fast exponential rise. If this small exponential rise were moved one quarter period later both the measured and computed wave would be in synch. again.

The initial values (spikes) at the initial breakdown of the first period are much larger than they were observed with the un-cut coil. They are also larger than the theoretical value of the current, that is based on the R, L and C that was assumed to explain the observed frequency and log decrement. It is therefore concluded that the observed spikes are not caused by the current (namely the magnetic field) but by the electric field that is caused by the collapsing magnetic field. It has to be understood that the current sensor is also an antenna that can pick up a large radio frequency field. Usually such spikes are disregarded as “electrical interference” imposed on the probe. A Rogowski coil will not show these spikes. In the present case, however, this electrical interference is one of the items that are of most interest.

The current sensor is terminated at the oscilloscope end by a 50 ohm resistor. The magnetic field vector induces a measuring current in the windings of the sensor and this measuring current produces a voltage drop across the 50 ohm resistor. This voltage drop is sensed by the oscilloscope and the produced trace is then interpreted as a current trace. Considering the small dimension of the sensor (1.0 cm diameter) one would ordinarily not expect that the same probe can efficiently act as an antenna for a 60 kHz rf (radio frequency) radiation. If, nevertheless, it is assumed that this happens, one has to admit that this electric field must be substantial. In the section concerning the mechanism of the fire extinguishment this will be further discussed.

For the same initial voltage on the capacitor, the current and frequency was increased just by making a cut in the disk coil. For an easier comparison the values observed for both coils are listed in Table 1:

	un-cut coil	cut coil
Voltage (V)	12,200	12,200
Current (A)	10,600	18,190
Frequency (kHz)	34.6	59.8
Resistance (Ω)	7.0×10^{-2}	1.6×10^{-1}
Inductance (H)	5.3×10^{-6}	1.8×10^{-6}
Initial Power (MW)	7.8	53

Table 1. Operational Conditions for Disk Coils

Note: for computation of the initial power the value of the positive peak of the first period was used not the spikes that may be caused by the electric field.

As already pointed out, resistivity and inductivity were deduced from the period and damping of the observed wave. As far as the period is concerned, its error is as large as the error in the measurement of time. The current sensor is not calibrated for absolute values; it measures only ratios. The error of measurement is determined by the capability of the oscilloscope to read voltages at the 1.0 volt level.

Consequently, the R and the L should be correct within a few percent. The current is computed with the above stated equations. However, some of the resistivity may not be ohmic. The damping increases substantially after the disk coil is cut. It is not reasonable to expect that some of the hardware should change its ohmic resistivity because a small gap is cut into the coil. What can happen, however, is that the two gaps, the main spark gap and the gap in the disk coil, change their respective values of resistivity.

It is a fact that the current almost doubles between the cut and un-cut version. In general it is expected that a gas discharge has a negative VI (voltage vs. current) characteristic. This means that at a higher current the voltage drop across the discharge becomes smaller (meaning the resistivity is smaller). This is not what was observed in the present experiment. However one needs to realize that these are large currents, and it is known that for large currents the VI characteristic of an arc goes through a minimum and then becomes positive. In other words the arc behaves from here on like a wire. This must be the case here.

The question is what form of power is it that constitutes the increased I^2R . Some of this I^2R is used to heat the plasma in the arc. The plasma will eventually be hot enough to radiate line radiation and some gray body radiation (specially in the IR), but it also will radiate rf (radio frequency). The frequency of this rf radiation is only 59 kHz. An efficient emission would require a sizable antenna, but the geometrical dimensions of the flame and the discharge are small. Therefore, while the radiation is generated it cannot be radiated away efficiently. The flame is only typically 20 cm away from the plasma, in rf-terms in the near field of the transmitter. That means the flame is exposed to most of the rf power. It is also exposed to optical and UV radiation. Which form of radiation is instrumental in the extinguishment mechanism will be discussed in the section devoted to this subject.

4. Firing Delays.

As can be seen in the previous section (see Figure II-1) there are two spark gaps in series. One of the two is the triggered main spark gap, the other one is the gap that is cut into the wire of the disk coil.

It is assumed, that during the charging of the capacitor, there is already a small current flowing. For such a current to exist, it would need to jump both spark gaps forming a discharge. This can only happen in the form of a (non-self-sustaining) corona discharge. Such a current is too small to deplete the large 4 μF capacitor to a measurable extent within the several seconds that pass when waiting for the trigger pulse. Once the trigger pulse is initiated an exponential buildup in the number of charge carriers in the main spark gap takes place.

Ordinarily it is not possible to run two arcs, or similar gas discharges, in series. In this special case the corona discharge in the gap of the disk coil acts like a limiting ohmic resistor for the build-up of the discharge in the main spark gap. However, this ohmic resistor changes with time rapidly. The consequence is that the current in the overall circuit keeps rising. The current in the gap of the disk coil experiences a $j \times B$ effect (j : current, B : magnetic field) and the discharge in this gap is apparently blown away once j reaches a certain value.

The main spark gap is subject to much smaller $j \times B$ forces; and therefore, it is not likely to be blown out earlier than the gap in the disk coil. Each time the

spark gap in the disk coil is blown out the main spark gap sees a fast interruption of the current flow. This means that the magnetic field of the current flowing through the main gap collapses quickly. Due to the induction law an electric field is thus generated, which bridges the main spark gap and, in essence, re-triggers it. After issue of a trigger pulse, this must be happening several times until the ends of the copper wire in the gap located in the disk coil are hot enough to produce sufficient thermionic emission so that the discharge in this gap can withstand somewhat larger $j \times B$ forces.

The overall effect is that there is a delay between the appearance of the trigger spark and the appearance of the main discharge. Figure III-12 shows a typical run monitored over a large time span.

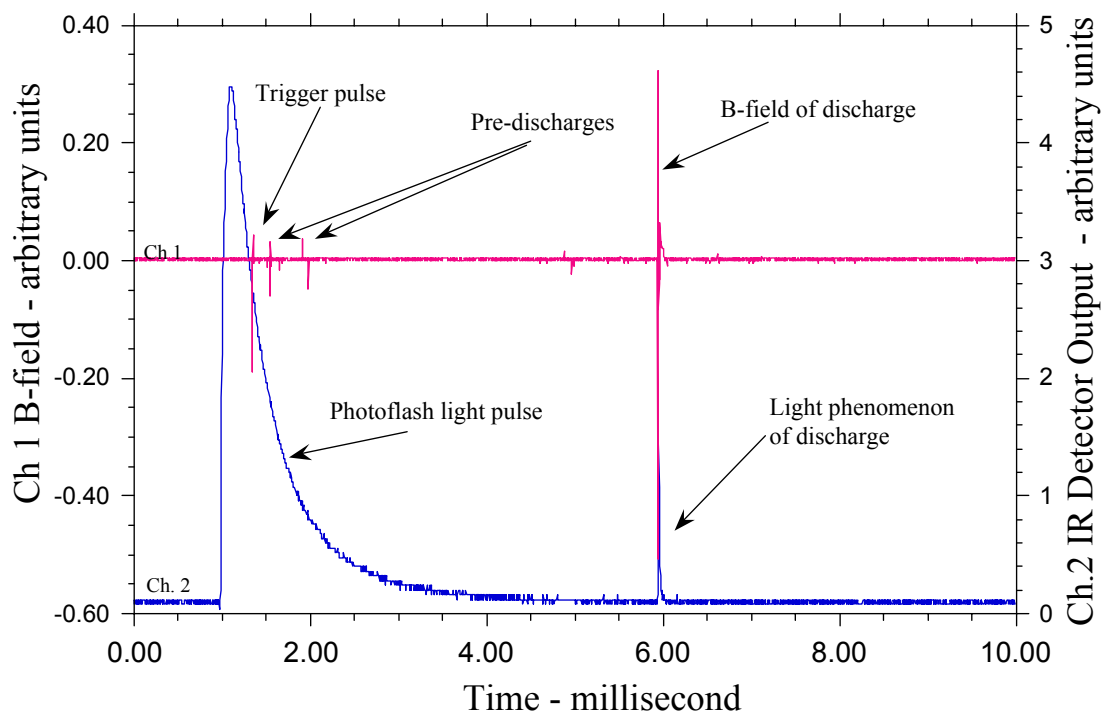


Figure III-12. Long Time Span Evolution of Discharge

As pointed out in the previous section, the ignition unit is activated by a light pulse traveling in a fiberoptic cable to this unit. Usually the light pulse is generated in the main control unit. For the test shown in Figure III-12 this unit was not used and the light pulse was generated by a regular photoflash unit. The output of this unit is monitored by an IR detector and is displayed and annotated as such on the oscilloscope trace (channel 2) shown in the figure. The same IR detector

also sees the trigger pulse on the main spark gap via radio frequency interference. The trigger pulse is also annotated. Channel 1 is the output of the magnetic field sensor. It also picks up the radio frequency caused by the trigger spark as well as the electromagnetic fields produced by the above discussed pre-discharges. The large pulses are the magnetic field of the main discharge (channel 1) seen by the magnetic probe and the light phenomenon (channel 2) accompanying the discharge seen by the IR detector.

As can be seen from these traces the time delay between the trigger pulse and the main discharge is 4.6 milliseconds. This time varies from shot to shot. It could be as short as 0.72 milliseconds, but the average is about 4.0 milliseconds. These pre-discharges are also visible on Figure III-12. On most occasions the pre-discharges are small as Figure III-12 indicates. There might be many more of these; but they are too small to be picked up by the magnetic probe. However, occasionally these pre-discharges can be substantial, large enough that the oscilloscope can be triggered by these signals. Figure III-13 is such an example. This happens only occasionally and most likely is related to the existing meteorological conditions.

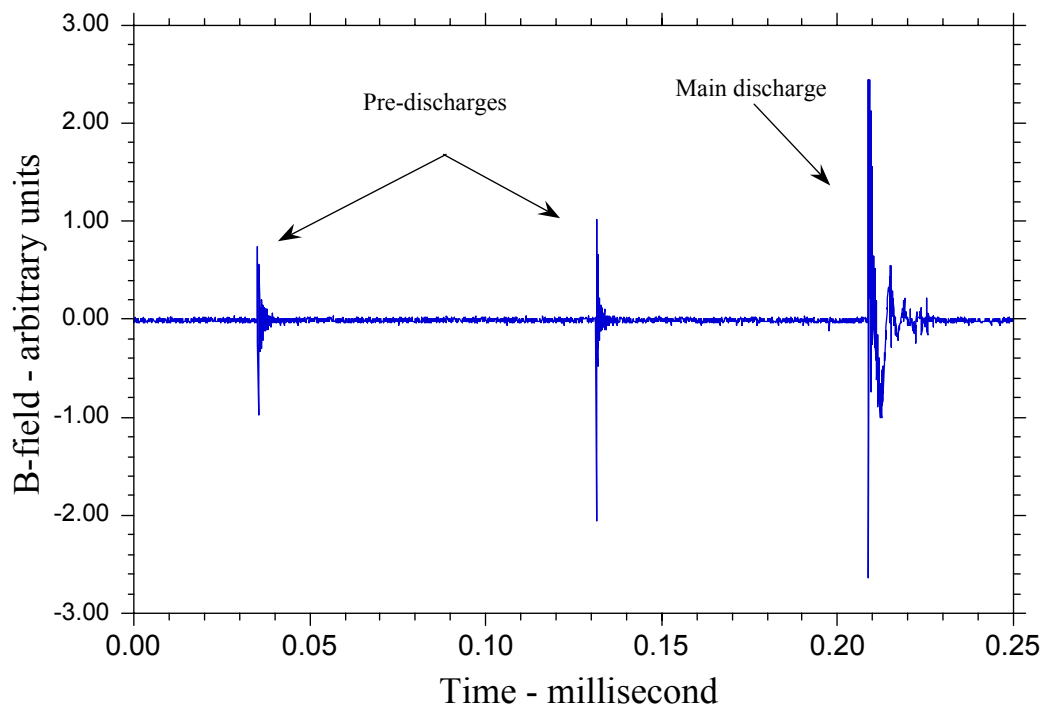


Figure III-13. Pre Discharges Detected by B-Field Probe

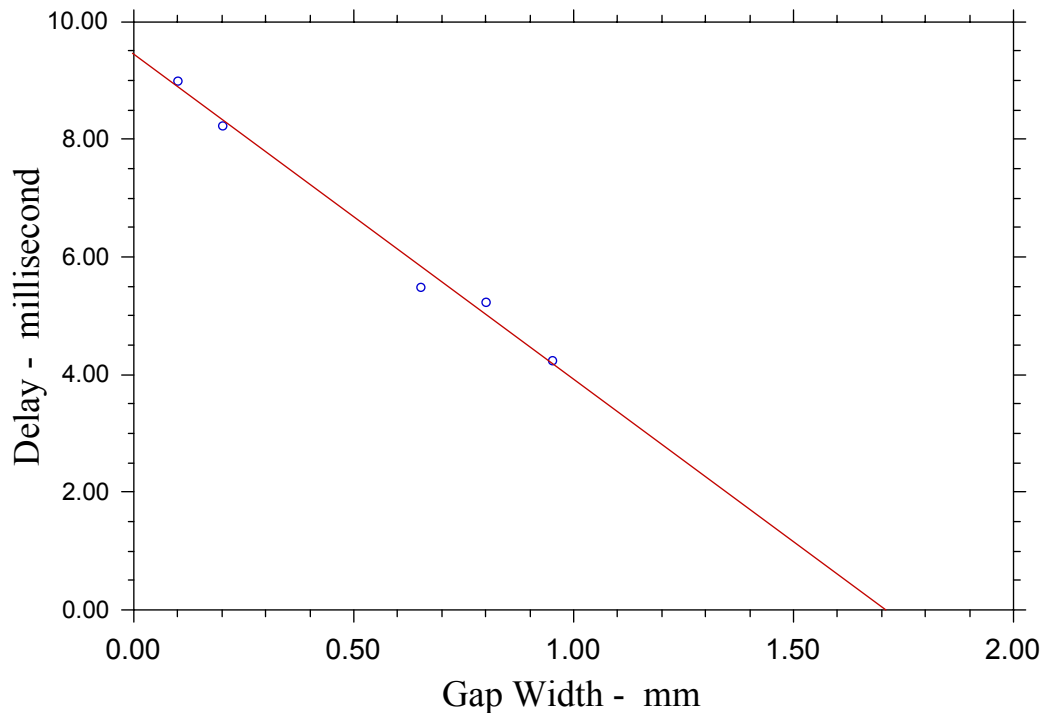


Figure III-14. Delay Between Spark and Discharge

The observed firing delay seems to be related to the width of the gap in the disk coil as well as to the applied voltage. Figure III-14 shows the delay between the appearance of the trigger spark and the main discharge as a function of gap width at a constant voltage (12.5 kV). As can be seen the delay is longer for small gaps than it is for larger ones. An interpretation of this could be that a blow-out at small gaps can form more often and each one will cause a delay, while at larger gaps a blow-out will not happen as often but those that do will have a better chance to grow into the main discharge.

Figure III-15 shows the delay as a function of voltage with constant gap width. One should bear in mind that this behavior is similar to an ionization chamber and the data points show the particular voltage when the non-self-sustaining discharge goes over into a self-sustaining discharge. In an ionization chamber such a transition is undesirable and is remedied by a quenching agent. In

the present system such a transition is desired. The “detected” particles are cosmic rays and naturally present free electrons.

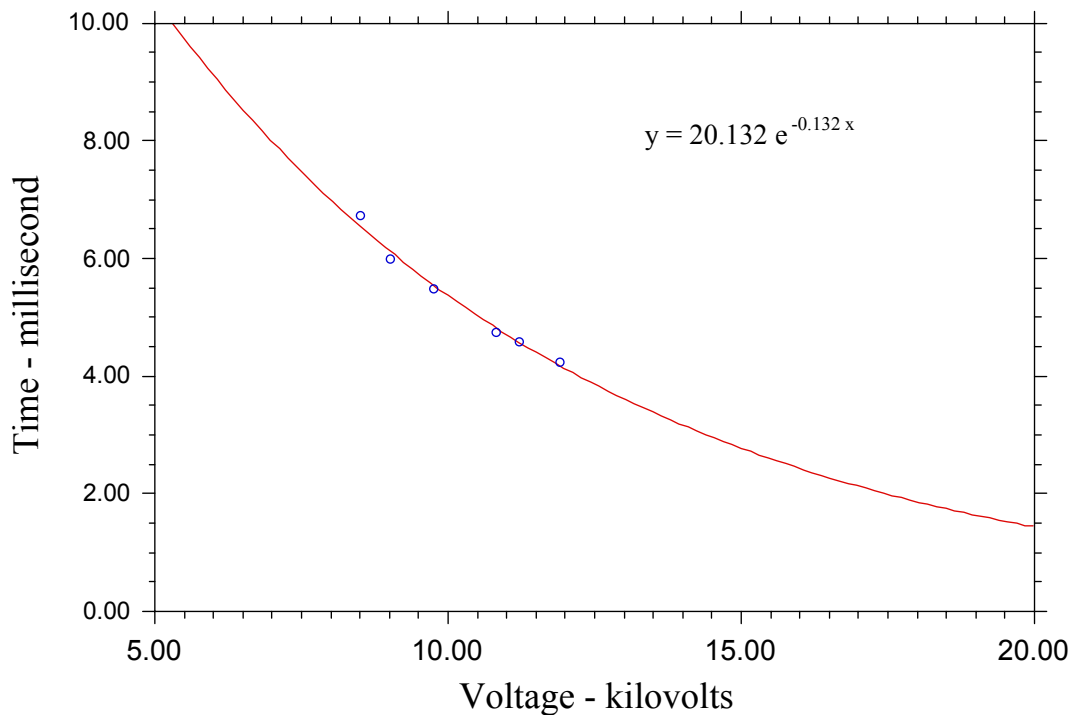


Figure III-15. Delay Between Trigger and Discharge

Such delays are of no consequence if an ongoing fire is to be extinguished. Still the rise times of the EM pulses are extremely short, typically 100 nanosecond or less and are not affected by the firing delays. The fact that these rise times are so short suggests that this technology could be used for explosion mitigation. Therefore it is a worthwhile task to reduce any firing delays to the μs level.

Section IV. Other Observations

1. Introductory Remarks

In this section some results are reported that may shed some light on the extinguishment mechanisms or suggests possible improvements of the device. It should be borne in mind that the present effort is a development effort for a fire fighting device not a basic research study. Therefore, the experiments reported in this section are of a qualitative nature and should be viewed as such.

2. Selection of Mechanisms

In order to get some insight as to which of the possible extinguishment mechanisms may be excluded from consideration the following experiment was performed. This experiment consisted in putting a barrier between the disk coil and the flame. This block was a piece of regular typing paper. It was taped at one edge to the device, but the other edge was free to move, similar to a flag.

The device used was a simplified version of the ten original devices. It consisted of a 0.5 μF capacitor operated at 25 kV. The same disk coil as used in the ten original units was also used here.

First a candle flame was extinguished. Figure IV-1 (a,b,c,d) shows the extinguishment sequence. These pictures are frames taken from video footage that was taken during the extinguishment experiment. Figure IV-1 (a) shows the piece of paper in place. The candle is also visible while burning. Figure IV-1 (b) shows part of the shot (the discharge is in the following called “shot”) and the candle is still burning. Obviously the part of the shot visible is the second field of the frame and the burning candle is in the first field of the same frame meaning; before the shot happened. Consequently the other part of the shot shows up as the first field in the next frame which is Figure IV-1 (c). The candle is extinguished; the still visible bright dot is the wick, which takes a few seconds to smolder out. Figure IV-1 (d) is the next frame after Figure IV-1 (c). The candle is out and the hot wick is still showing. At this point one has to conclude that the EM pulse can extinguish flames but not smoldering objects. This fact certainly is important for the explanation of the extinguishment mechanism. After the shot the paper moved somewhat, as indicated in the figure, but returned later to its original position.



Figure IV-1 (a) Extinguishment Sequence of Candle with Barrier



Figure IV-1 (b) Extinguishment Sequence, continued

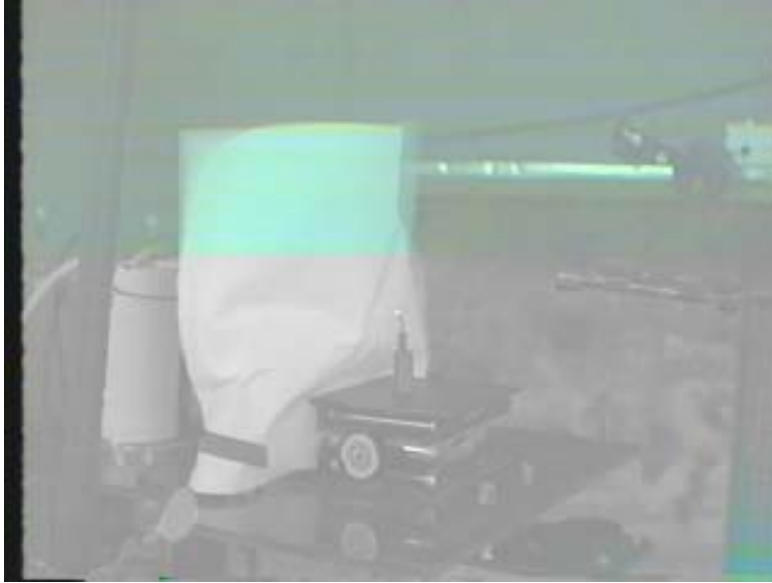


Figure IV-1 (c) Extinguishment Sequence, continued



Figure IV-1 (d) Extinguishment Sequence, end

A second experiment was performed with a propane flame. Figure IV-2 (a,b,c) shows the extinguishment sequence. Figure IV-2 (a) show the flame prior to the shot, while Figure IV-2 (b) shows the shot with the flame extinguished. Figure IV-2 (c) is the first frame after the shot. Again the paper moved somewhat after the shot but returned later to its original position. Again in this experiment also one edge of the paper was free to move.

It may be in order to make a few comments concerning the above experiments. They were not instrumented and can only serve as a screening process for possible extinguishment mechanisms. What mechanisms can penetrate a barrier and not knock over this barrier, but can extinguish a flame? What first comes to mind are electric and magnetic fields. Next come sound waves. They are known to penetrate walls, even if they have sound absorbing material in it. If the acoustic wave is a shock wave in air one might expect that the temporal change of pressure is large enough and over a sufficient distance (long wave-length) that the paper would be torn away. Finally an air puff (jet) would certainly knock over the paper.

It is therefore reasonable to conclude that these experiments suggest that the electromagnetic field is the main mechanism for flame extinguishment.



Figure IV-2 (a). Extinguishment Sequence of Propane Flame Through a Barrier



Figure IV-2 (b). Extinguishment Sequence, continued

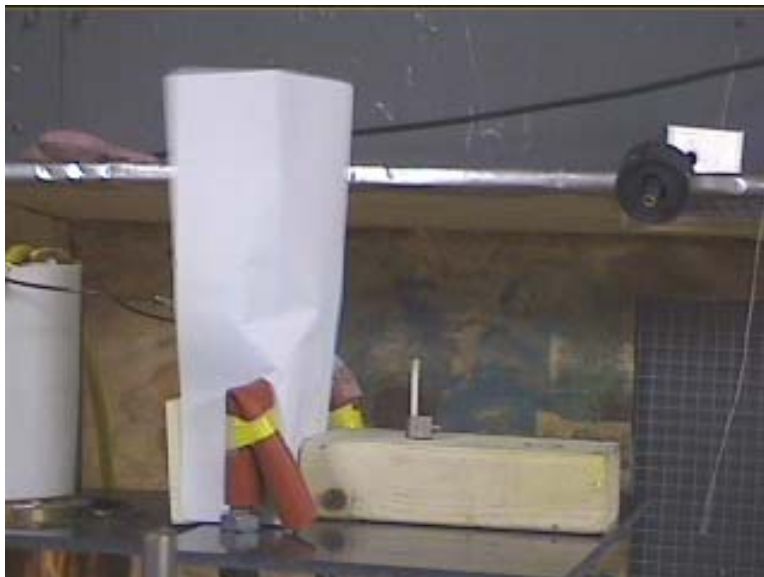


Figure IV-2 (c). Extinguishment Sequence, end

3. Extinguishment Time

The EM pulse is accompanied by a light phenomenon that is 100,000 to a million times brighter than the flame. Therefore any attempt to trace the flame intensity from the beginning of the experiment through extinguishment is met with great difficulties. Any detector sensitive enough to see the flame intensity will certainly be saturated by the light phenomenon. In addition, it has to be assumed that the intensity of the flame increases substantially in cases where the flame is not immediately extinguished. This is an experience obtained from many experiments and is described in “Section III. Operation of Device.”

It would be very useful to know how long the extinguishment lasts when the flame is immediately extinguished. The criterion for “immediate” is, for the purposes of the present effort, the case when there is definitely no flame visible in the particular video frame that follows the one that has the shot on it. This can be $1/30^{\text{th}}$ of a second later or only a very short time later, depending at what time the EM pulse was “caught” by the video camera. Experience shows that the larger the flame is, the more likely it is that hot clouds hover over the fuel and cause re-ignition of the fuel. Re-ignition can happen hundreds of milliseconds later.

Obviously a video camera based on NTSC is not very useful to detect whether the fire is extinguished immediately after the EM pulse is over. There are of course faster cameras available, but if one attempts to film microsecond events then synchronization is crucial. Ideally the camera would have to issue a trigger pulse, to indicate when the camera is ready to take pictures that have sub-microsecond exposure times. This trigger pulse would then be used to start the EM pulse. It is not inconceivable that this eventually can be accomplished, but that would require an additional development effort, which would be beyond the constraints of the present effort.

Consequently, a simple experiment that is capable of sub-microsecond synchronization was attempted. The set-up involves a Bunsen burner running on propane. One single unit of the device developed under the present effort is capable of extinguishing such a burner. In order to discriminate against the light phenomenon the flame was colored with sodium and viewed through a spectrometer that was tuned to the sodium-D line(s). Therefore, out of the total spectrum, that the light phenomenon puts out, only a tiny fraction is observed. This could be as small as

1/1000th of the full intensity. On the other hand the enhancement of radiation of the flame due to the addition of the sodium is also about 1000.

The seeding of the flame was accomplished by inserting a block of NaCl to the very edge of the flame. The sodium-D line(s) belong to the strongest lines known. Only a trace of NaCl will produce a strong emission. Therefore, it can be assumed that the sodium does not enhance or diminish the combustion process. However, it certainly will not emit atomic radiation when there is no flame present. This makes it a viable indicator whether or not the flame is out.

Figure IV-3 shows the time history of the EM pulse with no flame present. As expected, the PM tube is driven into saturation and recovers at microsecond #70. There is also a recovery at microsecond #50 before saturation occurs. As known from other experience the main light pulse is preceded by a weaker one. The negative blip at the beginning of the EM pulse (microsecond #50) is electrical interference suffered by the PM tube. This interference is caused by the strong rf radiation present when the EM pulse is turned on. The PM tube is very well shielded; nevertheless, some of the interference makes it through.

As can be seen in Figure IV-3 there is some light intensity present after the EM pulse is over. This signal cannot be explained by rf interference. This must be excited molecules of air. Nitrogen is known for this type of phosphorescence.

Figure IV-4 shows the flame seeded with sodium exposed to the EM pulse. Again the EM pulse is observed through a spectrometer that is tuned to the sodium-D lines. Again there is a negative blip that can be blamed on rf interference. The gap between the two light pulses is now zero. This can be explained by the strong absorption that the sodium-D line must represent against the continuous background of the light phenomenon. As in Figure IV-3 the PM tube recovers at microsecond #70, but the EM pulse is not quite over yet. It takes at least to microsecond #80 to disappear, as the steep decay in Figure IV-4 indicates. Therefore the light intensities observed after microsecond #80 must be due to the sodium radiation plus the excited air radiation. Subtracting Figure IV-3 from Figure IV-4 the sodium radiation alone is obtained (Figure IV-5). This assumption is a reasonable one. Based on our experience with the heptane pool fires, the EM pulse is very well reproducible. (See also Figure IV-14). Since the data were taken with a digital oscilloscope, this subtraction can be easily made. As can be seen in

Figure IV-5, the Bunsen burner is extinguished around microsecond #80 but recovers to the pre-pulse intensity by microsecond #100.

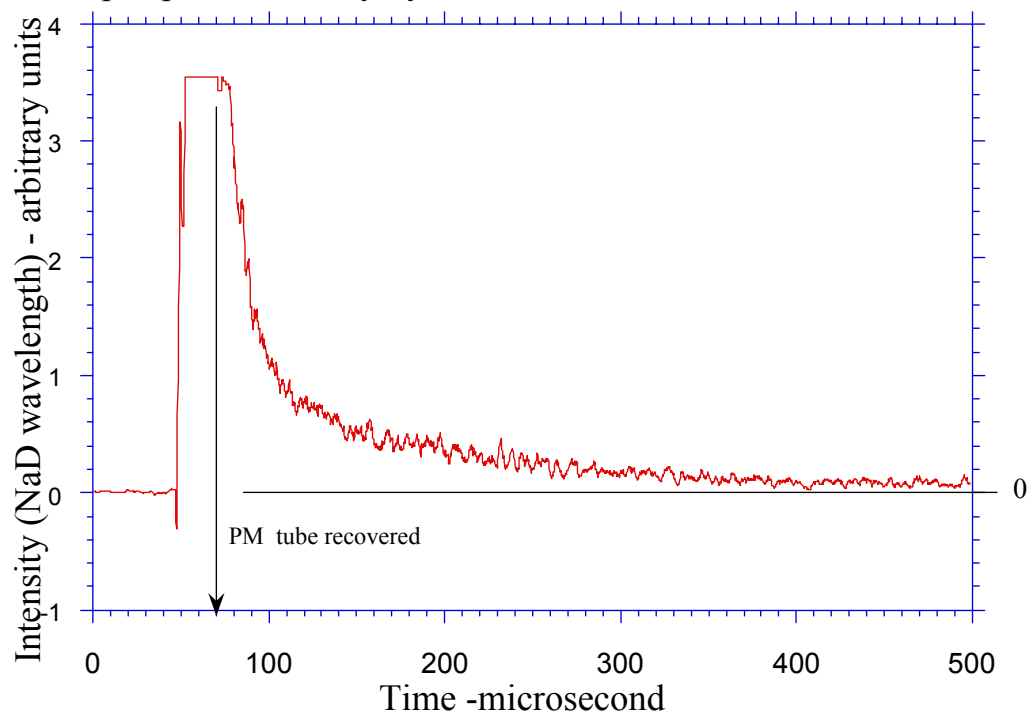


Figure IV-3. Time History of EM Pulse, No Flame Present

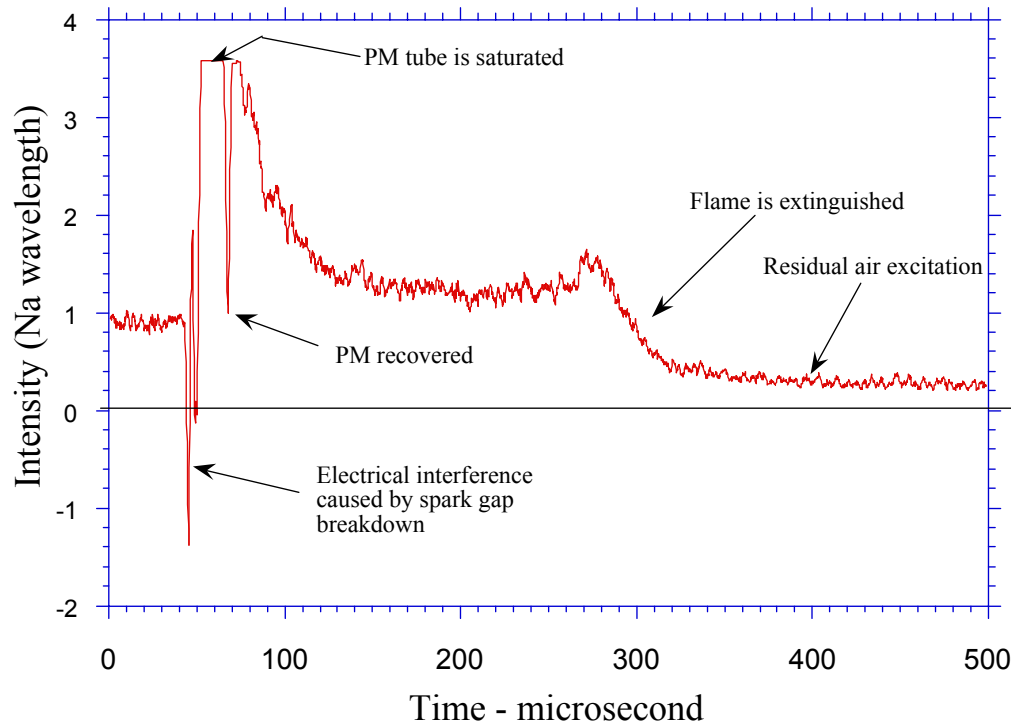


Figure IV-4. Flame (Seeded with Na) & EM Pulse

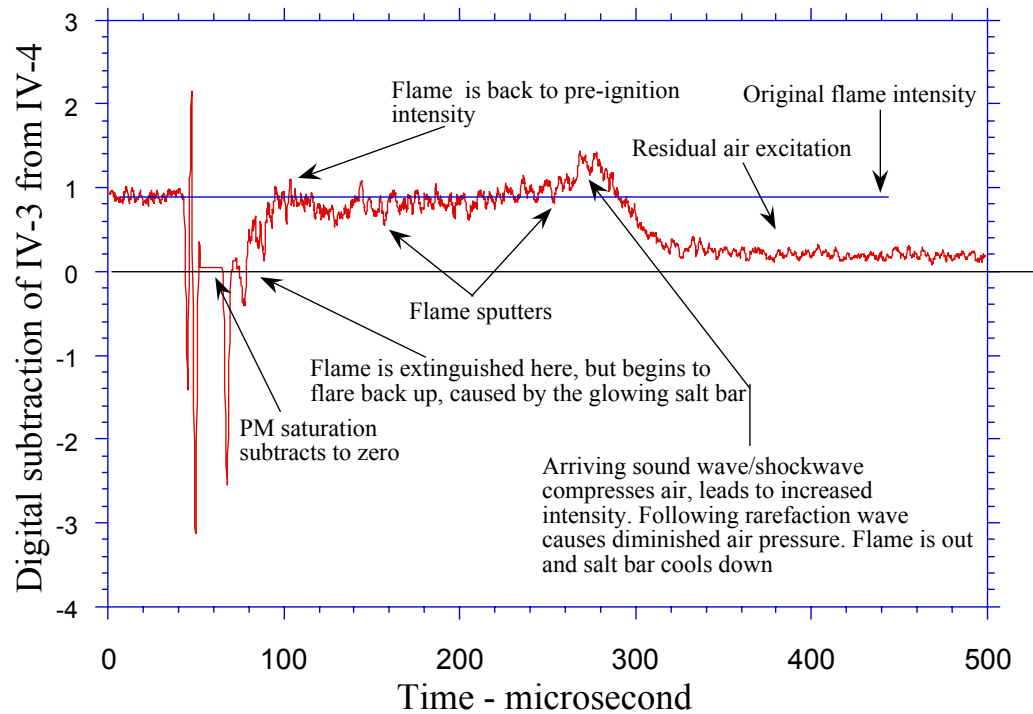


Figure IV-5. Discharge and Flame Minus Discharge Alone

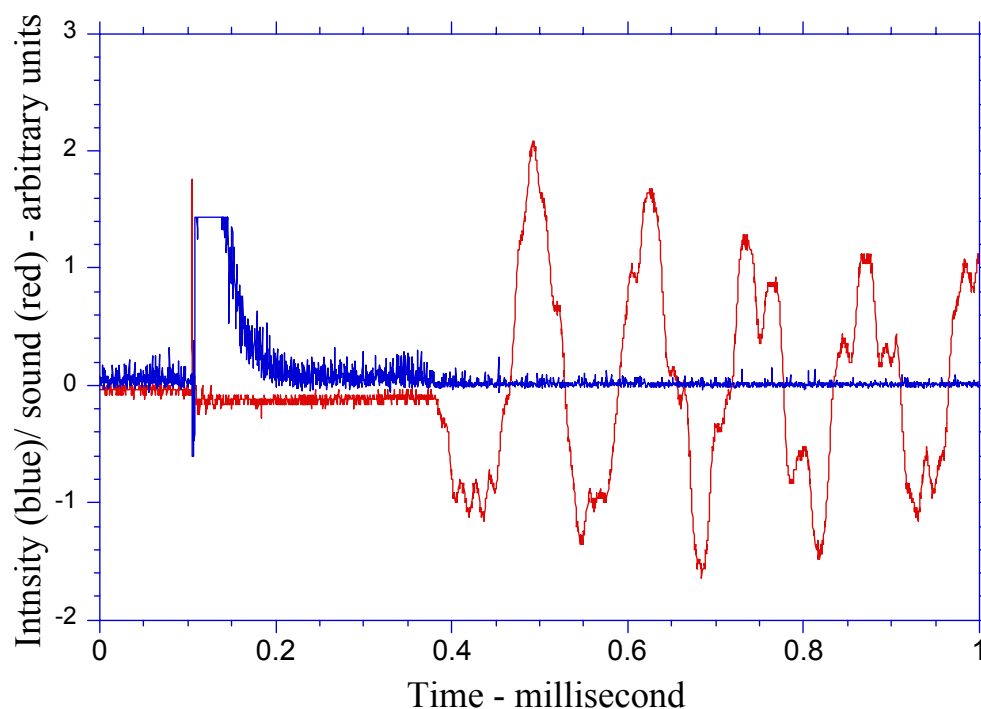


Figure IV-6. Acoustic Phenomenon

The question arises as to why there is a restart of the Bunsen burner. One should realize that the edge of the flame is touched by a piece of rock salt, that gets red hot in this procedure. There is sufficient heat capacity in this rock salt so that it will not cool down within a few microseconds. Therefore the restart can be blamed on the red hot rock salt. Also the chimney of the Bunsen burner is still hot. The latter effect disappears around microsecond #110. The consequence is that the fuel to air mixture is altered and the flame sputters, meaning it tries to extinguish but is restarted continuously by the still hot salt bar. The sound wave/shock wave arrives at microsecond #275. The air is compressed, the increased oxygen density causes the flame to brighten. (However, it is still sputtering.) Once the rarefaction part of the wave arrives that effect disappears and the flame is out for good. During the sputtering period the salt bar was not properly re-heated and is therefore no longer capable of re-igniting of the flame.

It might be interesting to present here the appearance of the arriving sound wave. Figure IV-6 shows the data of a different shot that has the sound wave on it. Its frequency is about 8 kHz and it is slightly damped. In the figure the front of the sound wave seems to be arriving later than the small peak at the end of the intensity trace. However, the transducer was placed at the same distance as the

flame was, but not immediately next to it. Therefore, it is possible that the sound wave that the transducer measured was somewhat slower with respect to the sound wave that hit the flame. The reason might be that the temperature of the air was different at these different locations.

Certainly the results of this experiment cannot be expected to be identical to the result that a similar experiment would produce when done on a heptane pool fire. First it is not possible to color the heptane flame because its temperature is too low. Secondly, the Bunsen burner is a forced flow flame, while the heptane pool fire is not. Once the combustion process of a Bunsen burner is interrupted, any hot cloud capable of restarting it will be swept away. In the case of the pool fire the hot clouds hover around for hundreds of milliseconds. For smaller pool fires these clouds are not strong enough to restart the fire. They may be present, one video frame later, but fail to restart the fire, as can be seen in the figures shown in "Section III. Operation of Device." Also, most of the time, the first frame of the video after the EM pulse will be blank. Therefore, the only conclusion that should be drawn from the above described experiment is that a flame exposed to an EM pulse can indeed be extinguished during the duration of EM pulse.

4. Field Patterns

Obviously, for extinguishment, the flame has to be exposed to some kind of field. This could be an electric field, a magnetic field, an air flow field (air puff) or a sound field (sonic or supersonic). In order to mark out the boundaries of such a field, a matrix of candles was used. Figure IV-7 is a still photograph which shows the basic principle of how such a matrix is constructed. In this figure only one of the 10 units is used. Its disk coil is visible at the right edge of the photograph.

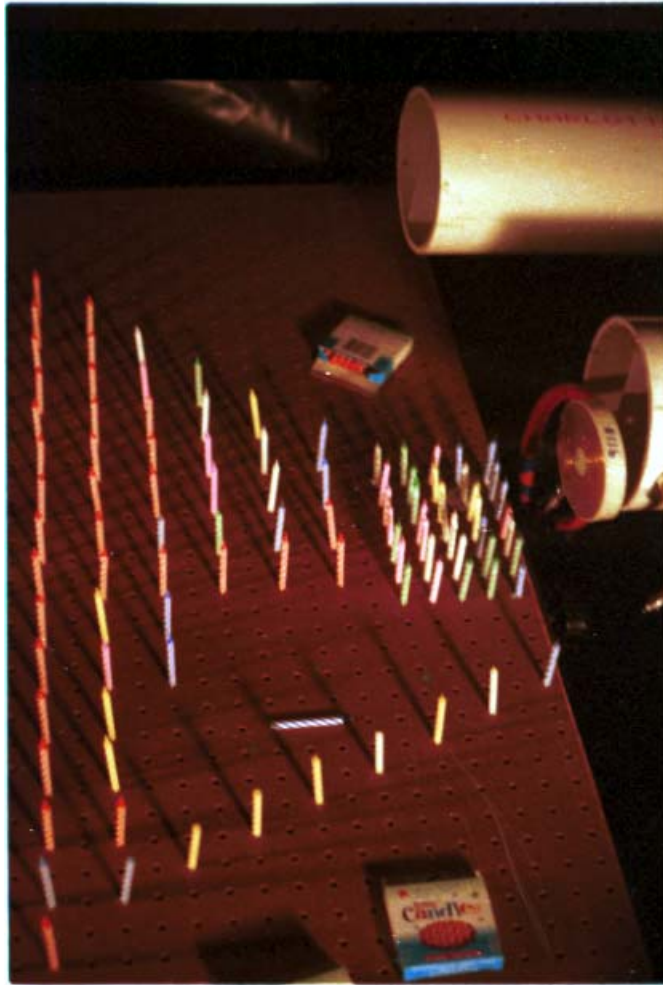


Figure IV-7. Candle Matrix

After a shot was fired another still photograph was taken, which is Figure IV-8. As can be seen the field (whatever it is) cuts a straight swath out of the matrix of burning candles.

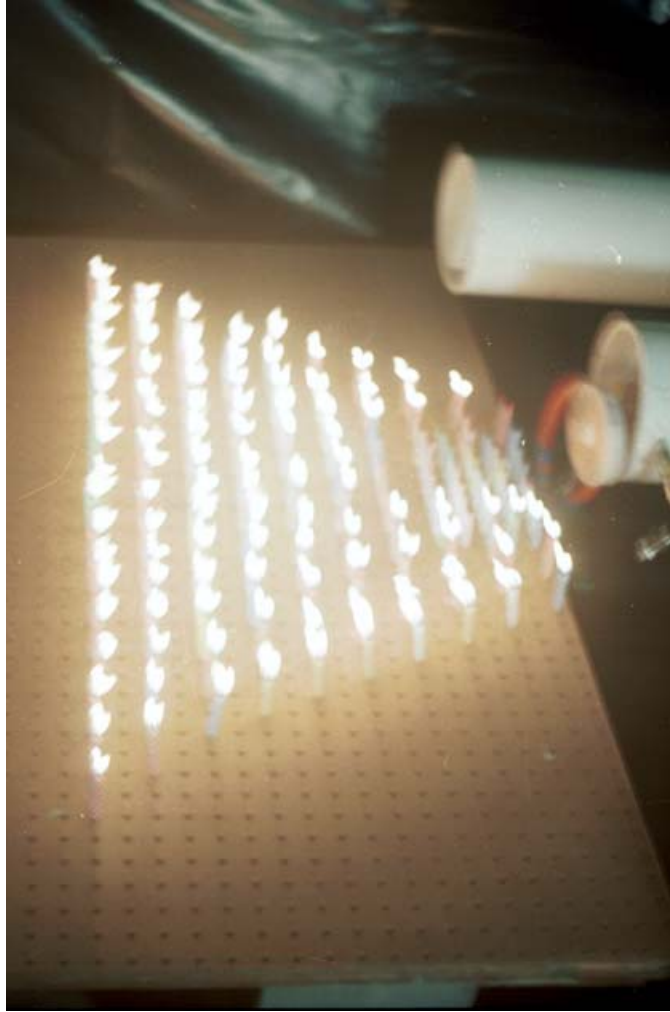


Figure IV-8. Candle Matrix After Single Shot

The matrix was restocked and two of the 10 units were fired side by side. The result is shown in Figure IV-9. The two disk coils are visible at the edge of the photograph. This time two areas in front of the disk coils were extinguished. The quality of this photograph is not very good, but it shows one important aspect, namely that there are two candles still burning between the two disk coils. This means that both coils cut a more or less rectangular swath. These two areas are separated by a location to which these fields do not extend.

Whatever the fields may be, they are certainly not point sources of spherical waves, like a point light source or a sound wave would be.

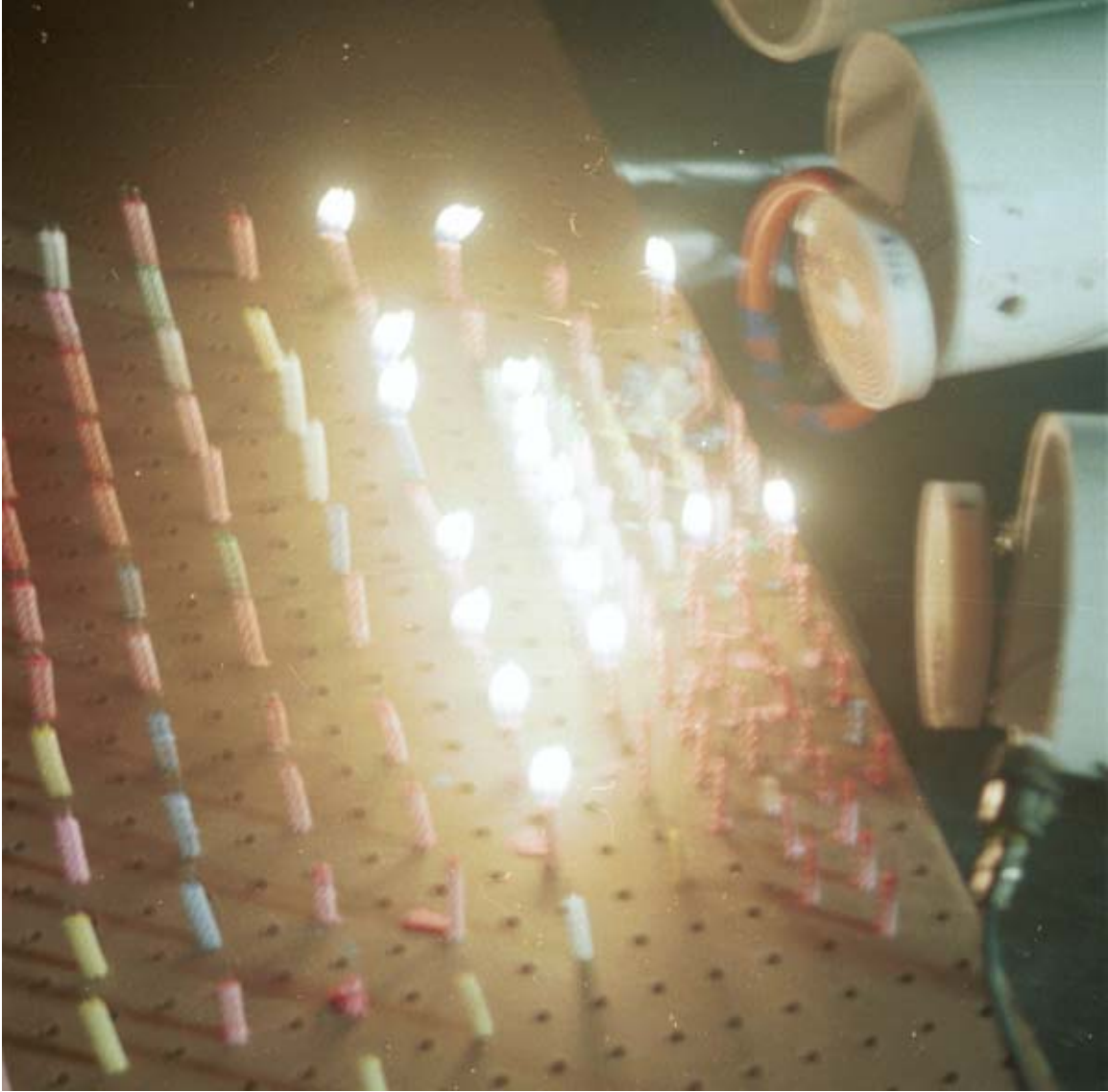


Figure IV-9. Candle Matrix After Double Shot

5. Field Influences

The fact that static electric fields influence flames is not new. In our experiments electrostatic fields are present during charging of the capacitor. Since one part of the disk coil is directly connected to the capacitor, this part will emit an electrostatic field. Its effect on the flame is visible. Starting at a minimum voltage (typical 12 kV) the flame will start to flicker. This persists until the shot is fired.

Magnetostatic fields also influence flames. Well known is the fact that a flame is bent out of a magnetic field gradient. Of course on the atomic level there is Zeeman splitting caused by the magnetic field and the Stark effect caused by the electric field.

The present effort is concerned with pulsed electromagnetic fields (EM pulses); and therefore, it may be worthwhile to mention a few observations, albeit only qualitative ones, that the EM pulse has on flames.

The following still photographs show very early results before the concept of the disk coil was established. Here a regular solenoid coil was used in conjunction with a 0.5 μ F capacitor charged to 10 kV. This configuration was unable to extinguish the flames. But it influences the shape of the flames. When transitioning to the later, more advanced units the light phenomenon accompanying the EM pulse was too bright and the interaction too fast; consequently such pictures could no longer be obtained by still photography. Nevertheless despite the fact that this configuration could not extinguish the flame, some interesting observation can be made.

Figure IV-10 shows heptane flames without the presence of an EM pulse. These are pool fires in watch glasses. For various reasons the flames always bulge together to two individual flames that overlap. Figure IV-11 shows the same flames exposed to a medium EM pulse. The light phenomenon is visible at the right edge of the photograph. The three red lines point to the location where the coil is placed.

In Figure IV-11 it appears that flames have spread out. But that may be misleading. These pictures were taken with an exposure of about a second. The pulse is manually fired and a short time earlier the operator opens the shutter (set at “B”) and closes it right after the shot. Nevertheless the exposure time is a second or longer. The duration of the EM pulse is 20 μ s. Since the flame gas can not possibly move a large distance during 20 μ s, the EM field must impress a momentum (a blow with a hammer) on the gas and it starts to move and keeps moving long after the pulse is over. From this consideration one has to conclude that the flames either are spread (very fast) by the field or they are jerked (also very fast) to certain positions, stay there for a while, and then are jerked again.

The next figure (IV-12) is taken with a larger pulse. This figure indicates that the flame may conform to a field that has the shape of a hemisphere with the coil in the center (where the three red lines meet). Finally, Figure IV-13 shows the largest pulse of which the system was capable. For this figure the flames were positioned closer to the coil. The fact that the flames are now over-exposed indicates that the flames are brightened by the pulse. The fact that the flames are brightened was also observed later when operating the 10 original units in unison (see “Section III. Operation of Device”). In Figure IV-13 it can also be seen more easily that flames bend toward the coil.



Figure IV-10. Heptane Flames not Exposed to EM Pulse



Figure IV-11. Heptane Flames Exposed to a Medium EM Pulse



Figure IV-12. Heptane Flames Exposed to a Strong EM Pulse

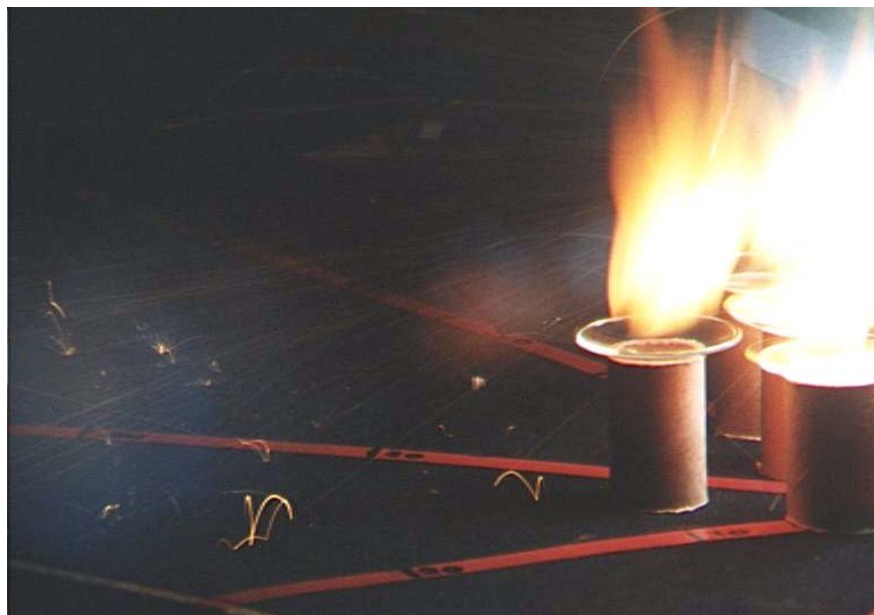


Figure IV-13. Heptane Flames Exposed to the Maximum EM Pulse

6. Pulse Reproducibility

As already pointed out in “Section III. Operation of Device” the phenomena going on during the discharge of the capacitor through the disk coil are rather involved. Therefore, it is in order to present here a demonstration of how well the discharges are reproducible. In the following we present the oscilloscope traces of five consecutive shots taken on the same day.

The traces show the magnetic field strength “B” (or better the induction) measured on the axis of the disk coil 30 cm away from the coil. Figure IV-14 shows these traces. Of course they should all be superimposed onto each other and they indeed are obtained this way. Fortunately with digital oscilloscope traces it is easy to shift those any desired amount. This was done here to be able to compare them visually.

Looking at the traces, only the one that is annotated “Basic trace” is not shifted. The next one is shifted by 1.0 arbitrary units and then each following one is shifted by an additional 0.5 arbitrary units.

The “Basic trace” of course hugs the zero line. The most striking features is that the B-field does not start at zero value at time zero. Since the B-field is in synchronization with the current, it should start with zero at time zero. This was discussed already in “Section III. Operation of Device.” It should be noted that in Figure IV-14 the zero point on the time scale is arbitrary. The true zero is when the discharge starts which is about $1.2\ \mu\text{s}$ later and is easily recognizable. The reason why it is delayed has to do with how the trigger was set at the oscilloscope and is of no consequence as long as the trigger setting is not changed between shots.

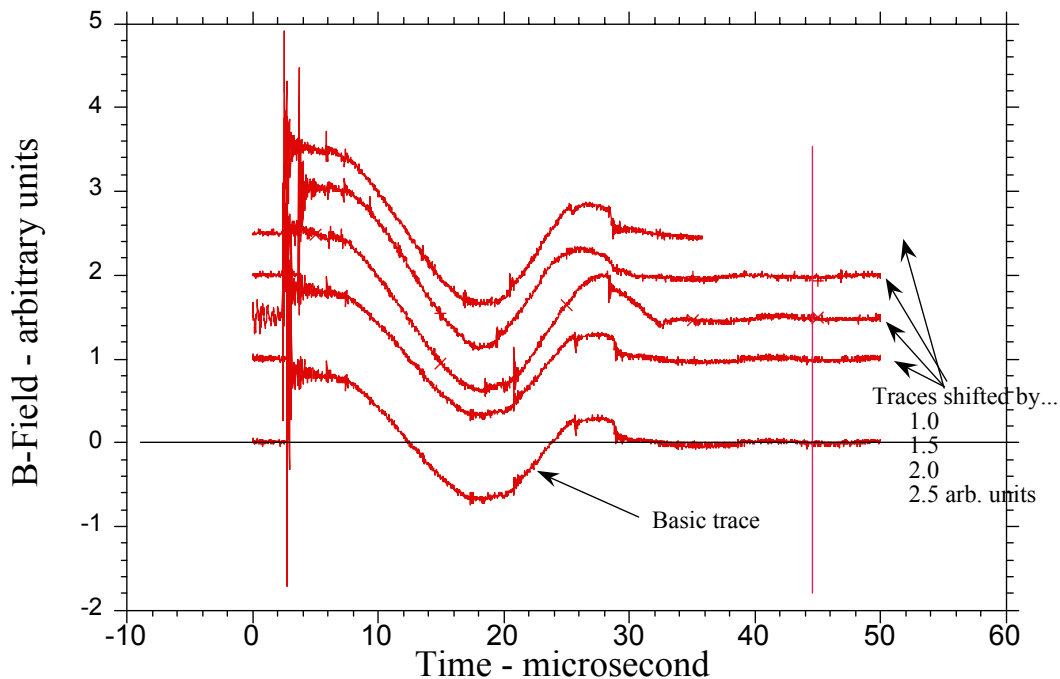


Figure IV-14. Reproducibility of Successive Shots

Examining the “Basic trace” one finds a short trace prior to time (true) 0. This should mean that there is no signal present other than the noise of the detecting device. This changes abruptly (within less than 100 nanoseconds) to the maximum value of the B-field. As pointed out before we assume that there is a low current arc already ongoing before time zero and the small trace prior the true zero point in time is not only noise but also this minute pre-current. Once the main spark gap is triggered, the current rises abruptly to its maximum. Necessarily the B-field is in synchronization with the current. As pointed out before that should

take $1/4^{\text{th}}$ of the total period, but it does not, since this is not controlled by the R and L of the circuitry.

There are four of these pre-zero traces visible. They mark the zero line for each shifted trace. There is one exception which is a decaying vibration rather than a straight trace which belongs to the trace that is 2.0 arbitrary units shifted. Interestingly this trace is also delayed by a fraction of a μs . These pre-discharges that cause delays were also discussed in "Section III. Operation of Device."

Another interesting feature is when the B-field collapses to zero. This must be when the voltage on the capacitor is decreased sufficiently so that it can no longer break down the main spark gap. All traces show an almost vertical break. The delayed trace shows it too but less pronounced. In all traces there are sharp momentary peaks at the second quarter of the period. If these disturbances are caused by electrical interference, the source for it must be a consistent one. It would be interesting to explore the reason for all this but that should be done in connection with a basic research study.

7. Spectroscopic Results

As pointed out above, due to cutting a gap in the disk coil, there is a plasma generated in the proximity of the flame to be extinguished. Whether or not the flame is immersed in the plasma depends on the distance between the disk coil and the flame. Such an immersion may be constructive or counter productive. Also the formation of this plasma is accompanied by a high intensity light phenomenon, which may or may not interact with the flame.

It is therefore beneficial to investigate the nature and composition of this plasma and so get some information that suggests whether an immersion is advisable. Therefore, the spectrum of the discharge were taken with a medium resolution spectrograph. The registration was photographic, using Tri-X 35 mm film.

The main species identified were lines of Cu I and Cu II (copper atoms and copper +1 ions) and bands of CN molecules. Since the disk coil is made from copper wire, the presence of Cu atoms and ions is understandable. The CN molecules were the only molecular species that could be detected. It is reasonable

to assume that the intense bands from CN molecules result from carbon in the nylon backing of the coil combining with nitrogen from the air.

There were none of the many molecule present that are usually observable in excited air. However, there were atomic nitrogen and atomic oxygen present. This suggests that the CN bands indeed came from the backing of the disk coil where the temperature was too low to excite the air. Consequently the CN band must be formed by chemical excitation. The arc itself must be very localized and sufficiently hot to generate copper atoms, copper ions, atomic oxygen and atomic nitrogen. A typical temperature for such an arc is around 20,000 K. The suggestion that this arc is very local comes from the fact that there are no excited air molecules present. In other words the air between the arc and the flame is at a temperature that is well below the above quoted value. This conclusion is important for a possible application to explosion mitigation. In this case it is not predictable where exactly the explosive reaction will start. Therefore large volumes of hot excited air would certainly be counterproductive to extinguishment.

The investigation reported here covered the wavelength range from approximately 250 nanometers to 670 nanometers. Table IV-1 lists the identified lines in this region.

Representative portions of the spectrum are presented in Figures IV-15 and IV-16. Figure IV-15 shows the shortest wavelength region that was examined. It contains the majority of the Cu II lines assigned. As such, this provides the evidence that the discharge produced a plasma. If the plasma was not as localized as assumed the free electrons produced could possibly interfere with the reaction mechanism of the flame.

Figure IV-16 shows an approximate 50-nanometer region (360-410 nanometers) with evidence for CN molecules which were the only molecules identified in the spectrum. The five band heads identified in this region correspond to the fine structure of the electronic transitions. The 388.34 nanometer head is the 0,0 transition, the 387.14 nanometer head is the 1,1 transition, etc.

In other regions of the spectrum second order lines intermixed with the first order spectrum were observed.

The question arises if investigation of other regions of the spectrum than quoted above might have revealed information that would contradict the conclusions made here. The IR spectrum is usually abundant with emission of molecules. Undoubtedly one would have picked up more molecules this way, coming from the halo around the arc. For this reason we took a survey with a low resolution spectrograph. The result is that the major emissions of the light phenomenon is at 650 nanometers and drops off fast going into the IR. In other words, if the halo molecules are there, they are weak and localized. For our purposes, namely to design the best device, it is sufficient to know that the plasma will not cause any problems if the flame is too close to it. We have extinguished smokeless gun powder as close as 8 cm from the disk coil.

Table IV-1. Identified Lines

254.4802	Cu II	259.8813	Cu II	261.8366	Cu I	266.6288	Cu II
268.9299	Cu II	270.0963	Cu II	270.3184	Cu II	271.3505	Cu II
271.8775	Cu II	272.1675	Cu II	273.7339	Cu II	273.9768	Cu II
276.6371	Cu I	276.9666	Cu II	279.9536	Cu II	282.4370	Cu I
285.8734	Cu I	287.7698	Cu II	288.2934	Cu I	296.1165	Cu I
299.7364	Cu I	301.0838	Cu I	303.6101	Cu I	306.3411	Cu I
307.3798	Cu I	309.3989	Cu I	309.9928	Cu I	310.8605	Cu I
311.6348	Cu I	312.6109	Cu I	312.8701	Cu I	314.0312	Cu I
314.2444	Cu I	314.6821	Cu I	316.9681	Cu I	317.9793	Cu II
319.4099	Cu I	320.8231	Cu I	322.3435	Cu I	322.4664	Cu I
322.6602	Cu I	323.1178	Cu I	323.3899	Cu I	323.5713	Cu I
324.3164	Cu I	324.7540	Cu I	325.2220	Cu I	326.6023	Cu I
326.8278	Cu I	327.3957	Cu I	327.7310	Cu I	327.9815	Cu I
328.2716	Cu I	329.0541	Cu I	329.2827	Cu I	329.2965	Cu I
330.7948	Cu I	331.7218	Cu I	331.9682	Cu I	332.9636	Cu I
333.5215	Cu I	333.7845	Cu I	334.9279	Cu I	335.4474	Cu I
336.5342	Cu I	338.0717	Cu II	340.2244	Cu I	341.3343	Cu I
341.580	Cu I	345.0332	Cu I	345.4686	Cu I	346.5401	Cu I
347.2141	Cu I	347.5999	Cu I	348.3761	Cu I	351.2121	Cu I
351.7039	Cu I	352.0031	Cu I	352.4231	Cu I	352.7482	Cu I
353.0383	Cu I	353.3746	Cu I	354.4963	Cu I	358.39	CN
358.59	CN	359.04	CN	359.9132	Cu I	360.2032	Cu I
360.9295	Cu I	361.0809	Cu I	361.3761	Cu I	362.1245	Cu I
362.4236	Cu I	362.732	Cu I	363.5916	Cu I	365.5859	Cu I
365.9353	Cu I	366.5735	Cu I	367.1953	Cu I	367.6878	Cu I
368.4672	Cu I	368.7438	Cu I	370.0536	Cu I	373.4180	Cu I
374.1242	Cu I	385.10	CN	385.47	CN	386.19	CN
387.14	CN	388.34	CN	393.3027	Cu I	402.2629	Cu I
404.3502	Cu II	406.2641	Cu I	408.0534	Cu I	410.4218	Cu I
412.3287	Cu I	415.24	CN	415.81	CN	416.78	CN
417.7758	Cu I	418.10	CN	419.72	CN	421.60	CN
424.8956	Cu I	425.9401	Cu I	427.5107	Cu I	432.576	O II
437.820	Cu I	441.554	Cu I	448.0350	Cu I	450.735	Cu I
450.9374	Cu I	451.3192	Cu I	452.5112	Cu I	453.0785	Cu I

453.9695	Cu I	458.697	Cu I	464.258	Cu I	465.1124	Cu I
467.472	Cu I	469.7490	Cu I	470.4594	Cu I	476.6729	Cu II
477.622	Cu I	479.400	Cu I	484.2290	Cu I	486.610	Cu I
501.6611	Cu I	503.436	Cu I	507.6173	Cu I	510.5541	Cu I
511.1913	Cu I	514.4120	Cu I	515.3235	Cu I	520.087	Cu I
521.8202	Cu I	522.0070	Cu I	525.052	Cu I	526.9988	Cu II
529.2517	Cu I	535.2666	Cu I	535.495	Cu I	536.0030	Cu I
539.162	Cu I	540.834	Cu I	543.205	Cu I	546.3138	Cu I
555.4935	Cu I	570.0240	Cu I	573.2325	Cu I	578.2132	Cu I
631.800	Cu II	644.849	Cu II	645.369	O I	672.312	N I

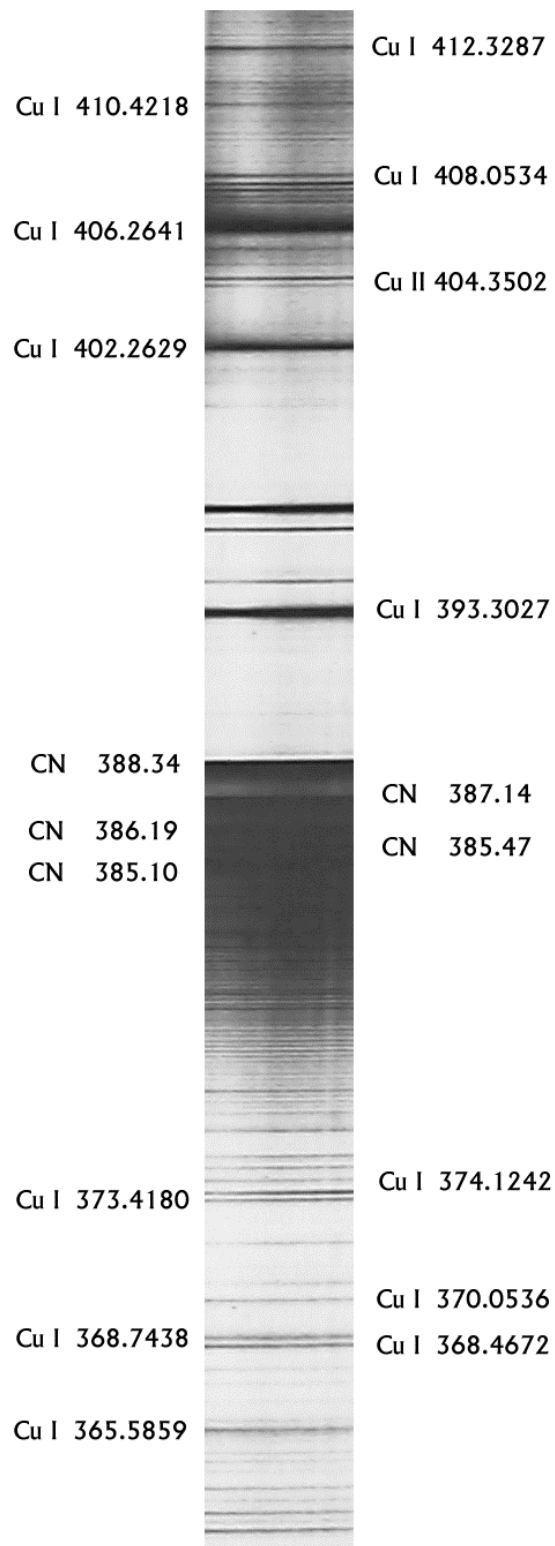


Figure IV-15. Shortest Wavelength Region

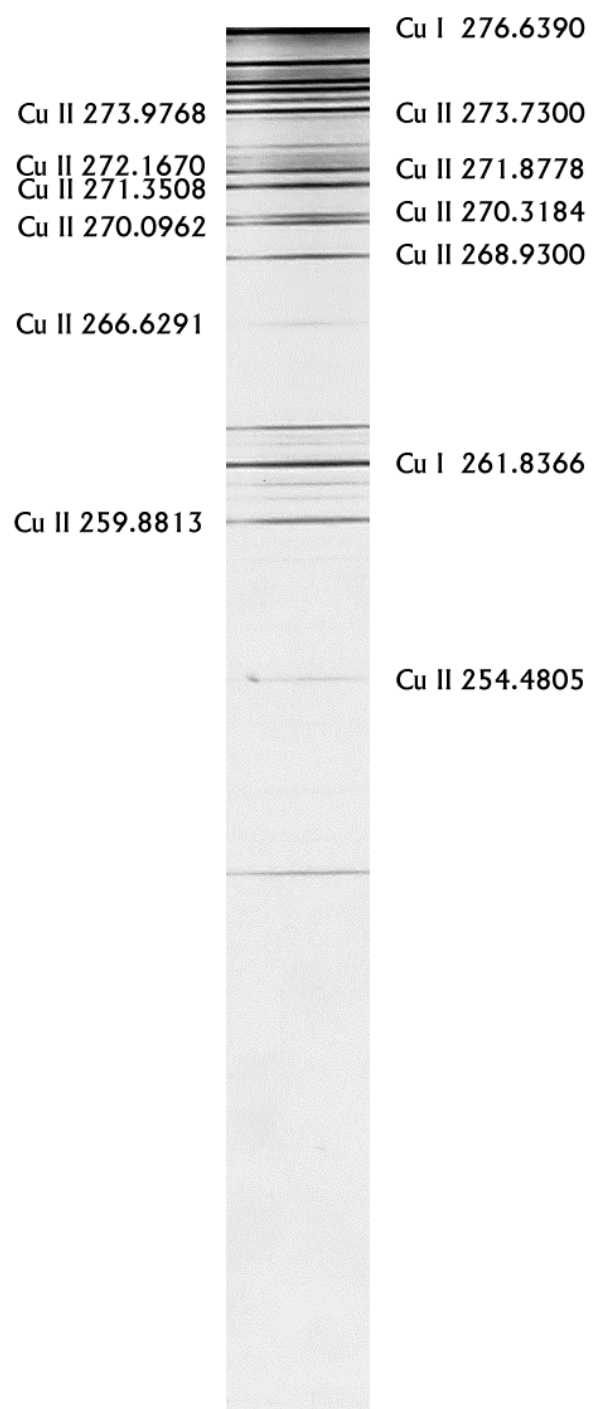


Figure IV-16. Region 360-410 Nanometers Showing Evidence for CN Molecules

Section V. Explosion Mitigation Research Device

1. Introductory Remarks

The present Phase II effort was initially concerned with extinguishment of already ongoing fires with an electromagnetic pulse (EM pulse) only. No water or chemicals were used. This goal was successfully achieved. Due to the experience gained with this effort there are indications that this new technology could be used for explosion mitigation. It was therefore decided to extend this effort towards this aim.

The main issue concerning mitigation of explosions is whether or not the fact that explosives provide their own oxidant (or other reaction partner) makes it impossible to extinguish an ongoing explosion with an EM pulse. It could be reasonably expected that, if there is a flame, EM fields or EM radiation can interfere with the combustion mechanism and bring it to a standstill. We say “reasonably expected” since during this Phase II we have demonstrated that for already burning flames this is indeed the case. On the other hand we have also established the fact that the EM pulse will not extinguish smoldering solid material.

The technology developed under the present effort was aimed at extinguishment of ongoing heptane pan fires. In addition to demonstrating that such a process is possible at all, an additional goal was to determine if the process can be scaled up to fires of an appreciable size.

Obviously in situations requiring explosion mitigation only a tiny amount of explosive should be consumed prior to the point of time when the explosion is extinguished; the bulk of the stored explosive should be untouched. Therefore, in contrast to the goal of extinguishing a large fire, now only a tiny fire needs to be extinguished, albeit in a very short time. The consequence is that these types of experiments can be done with very small amounts of dangerous material. As long as after extinguishment even a trace of the dangerous material is left, the point has been shown. There is no need to have a large amount of material waiting, that is expected to stay untouched.

In order to explore whether the technology developed under the present effort could be used for explosion mitigation, experiments involving smokeless gun powder were performed.

2. Simulation Experiments

Naturally it was attempted first to use the new technology as developed so far. This entails the use of the 10 prototypes used for extinguishment of already burning fires as they are. These units will be referred to in the following as *original units*. It should be borne in mind that these units suffer from extensive firing delays (see “Section III. Operation of Device, 4. Firing Delays”); however, as can be seen in the following, these units are adequate to extinguish burns of smokeless gun powder in due time. Obviously it is advisable to gain some experience with the relatively slow burning smokeless gun powder, before one attempts extinguishment of faster burning material.

The experience needed to be gained is to assure the proper functioning of the electronic devices that are responsible for the detection of the incipient burn, and their reaction to it, causing the firing signal. Also the time between detection and issuing the firing signal should be controllable by the experimenter. This is done by a variable delay generator. And last but not least the delay between arrival of the firing signal and the actual firing should be measured at all times. Once the reliable acquisition of these parameters is established, these electronic units can be used in connection with a faster device without requiring further development.

For demonstration purposes the gunpowder is laid out in a straight line, a train. The intensity of the burning powder train will be monitored by an IR detector of our own design. This detector will issue a trigger pulse once the intensity of the burn reaches a certain level. The detector(s) can be stationed along this train (using fiber optics) and so monitor at which location the burn has been stopped. For the study of explosion mitigation this will be especially advantageous.

In such a set-up the amount of dangerous material can be kept to a minimum. The smokeless gun powder train will simulate explosive material quite well. The train will burn slower but the response time can be kept as short as desired. This is done by letting the burn build up and using the delay generator to set the response time. A short response time necessary for explosion mitigation can so be demonstrated. Also it is possible to increase the burn velocity of smokeless

gun powder by various chemical treatments, although this should be done on a range rather than in a laboratory environment. Nevertheless, the transition from gun powder to explosive can so be made more safely.

For the powder burn in the laboratory a burn chamber is required which is capable of containing the burn if something should go wrong and the entire material is consumed. This burn chamber was designed and constructed under the extended effort. As pointed out above the time between ignition of the powder train and the time when it reaches appreciable intensity will be long compared to an evolving explosion. Therefore, it is obviously easier to extinguish such a burn than to interrupt an evolving explosion. Consequently, in these simulation experiments, it has to be shown by demonstration that:

- a. An ongoing burn can be detected at a low flame intensities.
- b. The time between detection and reaction to it with the EM pulse is short.

To do this, the burn needs to be detected at low intensities but the reaction time to it can be artificially delayed with a delay generator until the burn has reached an appreciable intensity. Since such a delay is variable, it is possible to determine the minimum intensity at which extinguishment still can be achieved. Also by reducing this delay time to the very minimum that the device can handle, it can be shown that the reaction time is sufficiently short; equal to what will be required in a real explosion.

The original units store a relatively large amount of energy in order to be able to extinguish a reasonable large flame. The reaction time to the fire is of no consequence since the fire is already on-going. The consequence of storing a large amount of energy is that there are large current rise times involved. In addition firing delay times exist. For example, there is a 340 μ s delay in the ignitor unit. This is the time that passes between the arrival of the output pulse of the IR detector and the appearance of the trigger spark at the spark plug. This time is too long for the purposes of explosion mitigation. We also discovered that the particular design of the coil that produces the electromagnetic pulse introduces an even larger delay, namely 4.5 milliseconds. Again for use as a fire extinguishment system for already burning fires, this is of no consequence, but for explosion mitigation this is not acceptable. Yet for studying the smokeless powder burns the original units are adequate.

3. Simulation of Explosion Mitigation with the Original Units

Therefore, in order to explore possibilities to reduce these firing delays to acceptable levels, some modifications were made on the original devices. These modifications mainly consisted in increasing the gap in the coil and polishing the electrodes in the main spark gap. Also, based on the experience with the pool fire, three units were fired at preset delay times for extinguishment of the powder burns.

In this way a burn of smokeless gun powder (in pellet form) was extinguished. These pellets have a diameter of 1.0 mm and a length of 2.25 mm. Of course smokeless gun powder has its oxygen built in.

Figure V-1 shows the light intensity vs. time of the smokeless gun powder (pellets) burn. The fire became detectable at millisecond #1.8. However, as indicated in the figure, the trigger threshold was set at a slightly higher level than the minimum detectability. There was a firing delay of 1 millisecond and the fire was extinguished from an appreciable intensity to zero at millisecond #4.2. In evaluating this figure one may wonder why it took 0.8 milliseconds between actual firing and extinguishment. The same explanation may hold, as given for the Bunsen burner in “Section IV. Other Observations.” The fire may have been destabilized by the first shot, but it extinguishes only when the glowing, but not flaming, gun powder particles became cold enough to support maintaining a flame. It should be borne in mind that the EM pulse can only extinguish flames, not glowing solid particles.

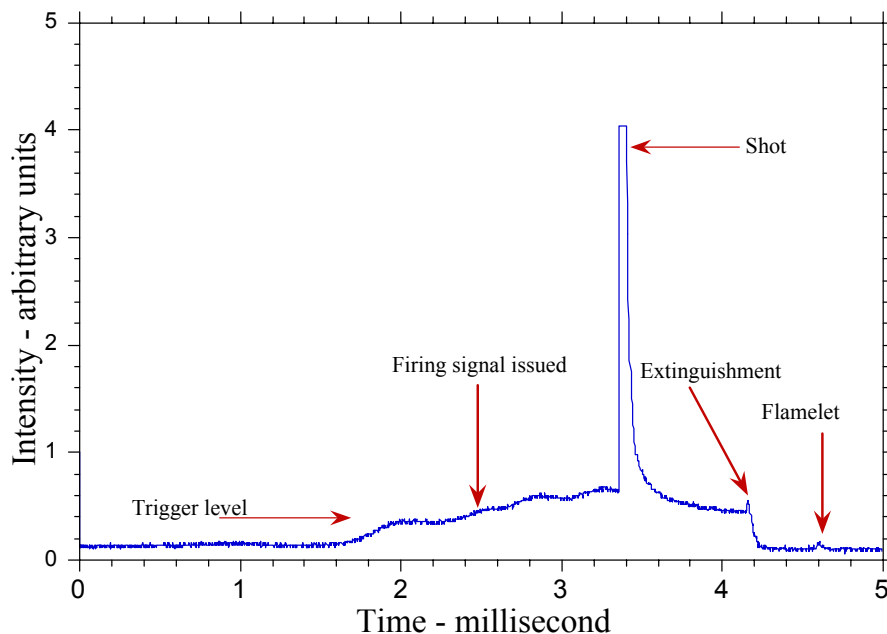


Figure V-1. Pellet Burn

At the end of the exponential decay of the final extinguishment, there is again a small flare-up. This happens also in the Bunsen burner case, and the explanation for it might be similar.

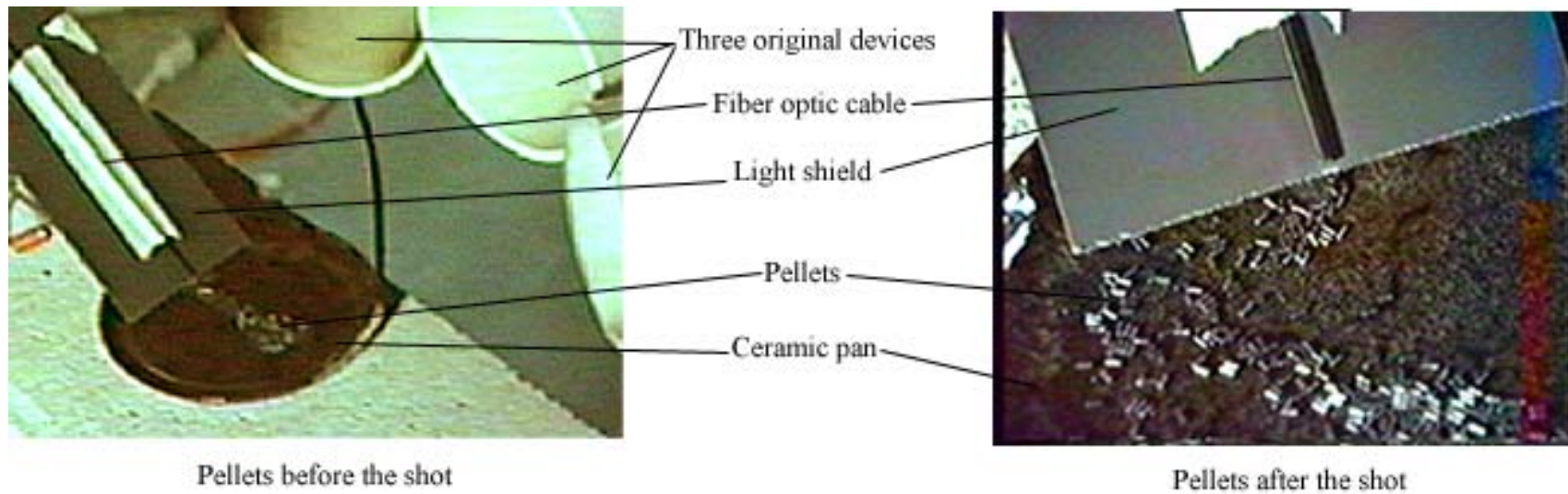
However, as it turns out the story is not over yet. There is a small peak after the extinguishment that shows there is still some activity, which must be a small flame (flamelet), since a glowing solid particle will not go on and off in such a short time interval.

Inspecting the video tape that was run during the experiment, actually reveals that the fire restarts one more time to the full intensity and gets extinguished again by the second and third shot. Unfortunately, the oscilloscope was out of its recording range and there is no oscilloscope trace for the second event. Nevertheless the video tape shows it. After the experiment, the remaining powder was re-ignited artificially by hand to make sure the extinguishment took place due to the EM pulse and not due to exhaustion of fuel.

Figure V-2 (a through i) is a sequence of frames picked out of the video tape of the smokeless gun powder (pellets). Figure V-2 (a) shows the set-up. Before the shot the pellets are arranged in a ceramic pan in a train in the form of a “v.” This is done to encourage an increase of the burning speed after the initial

ignition has been accomplished. The small end of the “v” is covered by a light shield. There are some pellets and an electrical ignitor under this shield. The reason for the shield is to hide the incipient burn from the optical fiber until the burn has a certain intensity. The optical fiber is visible on top of the light shield. This fiber is connected to the IR detector which acquires the signal of the part of the burn that becomes visible as soon as it comes out from under the light shield. The three circular structures visible in the photograph are the front ends of the three original devices used for this experiment. The other photograph in V-2 (a) is taken closer to the pellets, which are now discernible. This image was taken after the three shots were completed--meaning the fire was extinguished. It shows that the majority of the pellets were untouched. Some of them were moved by the air puff, but most of the train is still intact.

Figure V-2 (b) shows the set-up before firing the first shot. Figure V-2 (c) shows the beginning of the burn prior to firing the first shot. Figure V-2 (d) caught the first shot on the second field of the frame, which also contains the image of the burn prior to the first shot. Figure V-2 (e) shows the second field of the frame that contains the first shot. Figure V-2 (f) is a frame after the first shot.



Left photograph shows the set-up before a shot was fired. The right photograph is a close-up after the three shots were completed and the burn was extinguished

Figure V-2 (a). Extinguishment Sequence, Pellets

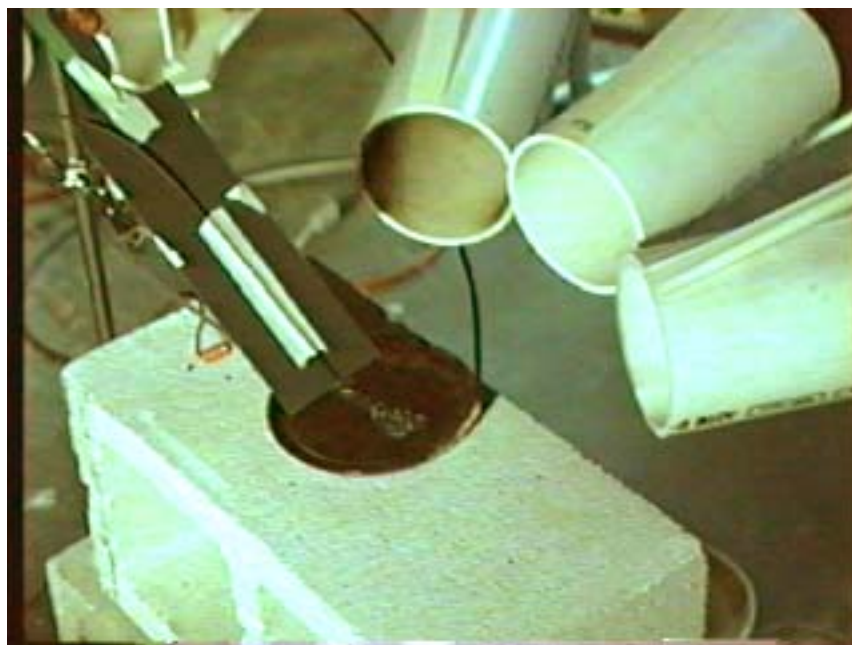


Figure V-2 (b). Extinguishment Sequence, Pellets continued



Figure V-2 (c). Extinguishment Sequence, Pellets continued



Figure V-2 (d). Extinguishment Sequence, Pellets continued

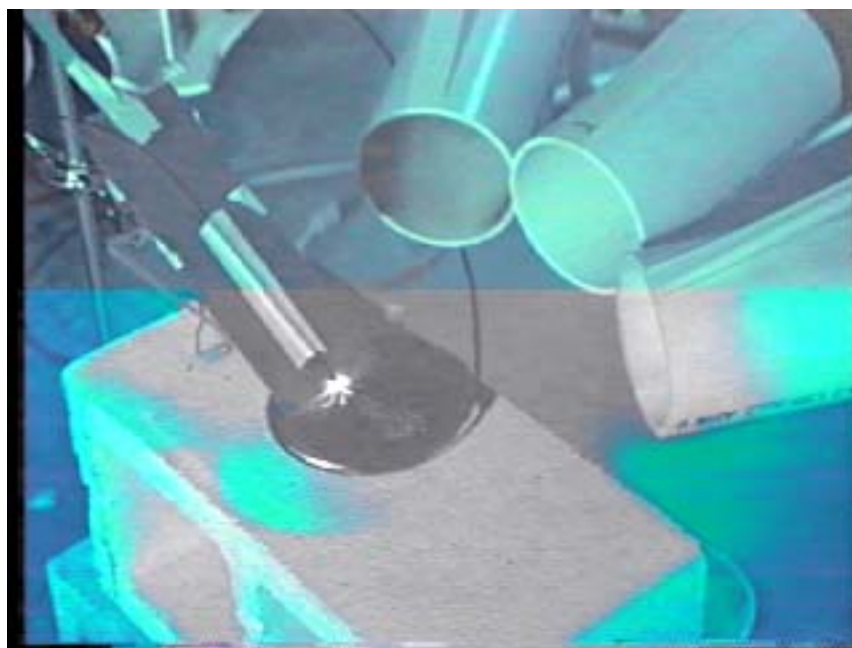


Figure V-2 (e). Extinguishment Sequence, Pellets continued

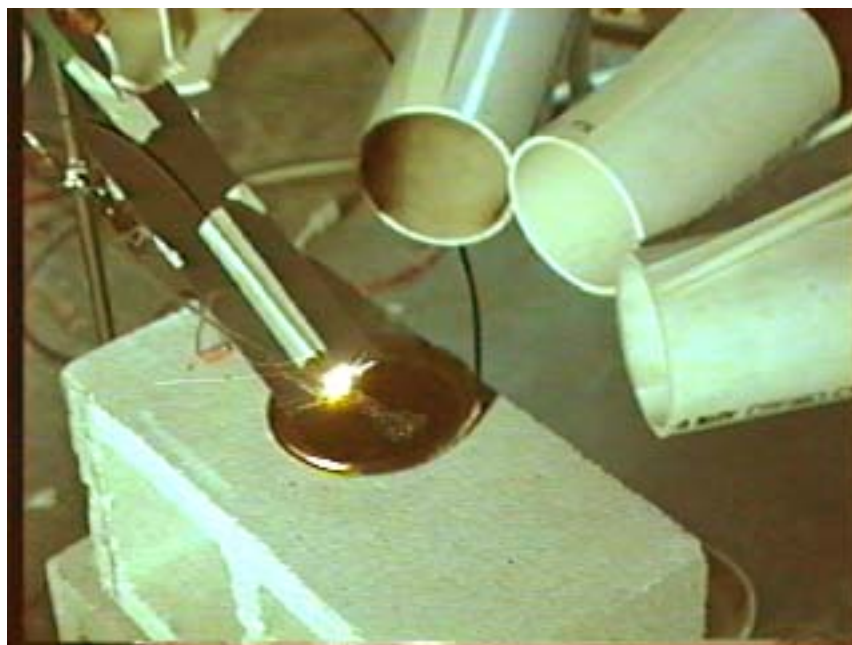


Figure V-2 (f). Extinguishment Sequence, Pellets continued



Figure V-2 (g). Extinguishment Sequence, Pellets continued



Figure V-2 (h). Extinguishment Sequence, Pellets continued



Figure V-2 (i). Extinguishment Sequence, Pellets end

The oscillogram in Figure V-1 proves that the fire was out after the first shot. Therefore what is seen in Figure V-2 (f) is the beginning of the re-ignition. In Figure V-2 (g) the flame has grown even more. But this figure also contains the next shot. Figure V-2 (h) shows the last shot and Figure V-2 (i) shows the next frame after the last shot was over. As can be seen there is still some light intensity present, but that must be a glowing solid particle rather than a flame.

To investigate the latter statement a new experiment was performed, this time using smokeless gun powder in “powder” form. The particles of this powder are typically only 25 micrometers in size. Therefore an individual particle glowing will cease glowing before the next video frame is taken. The set-up of this new experiment was similar to the sequence seen in Figure V-2, with the exception that no light shield was used. Therefore there was no place for glowing particle to hide below such a shield. Figure V-3(a through e) shows the extinguishment sequence of the small particle powder version of smokeless gun powder.

Figure V-3 (a) shows the burn before the first shot. Figure V-3 (b) shows the frame that contains the shot as well as the still burning flame that was imaged before the shot. Figure V-3 (c) contains the first shot in the second field and shows that the fire is now extinguished. Figure V-3 (d) is the following shot, that was of course unnecessary. Finally, the next frame is completely dark; therefore, it is not shown here.



Figure V-3 (a). Extinguishment Sequence, Powder

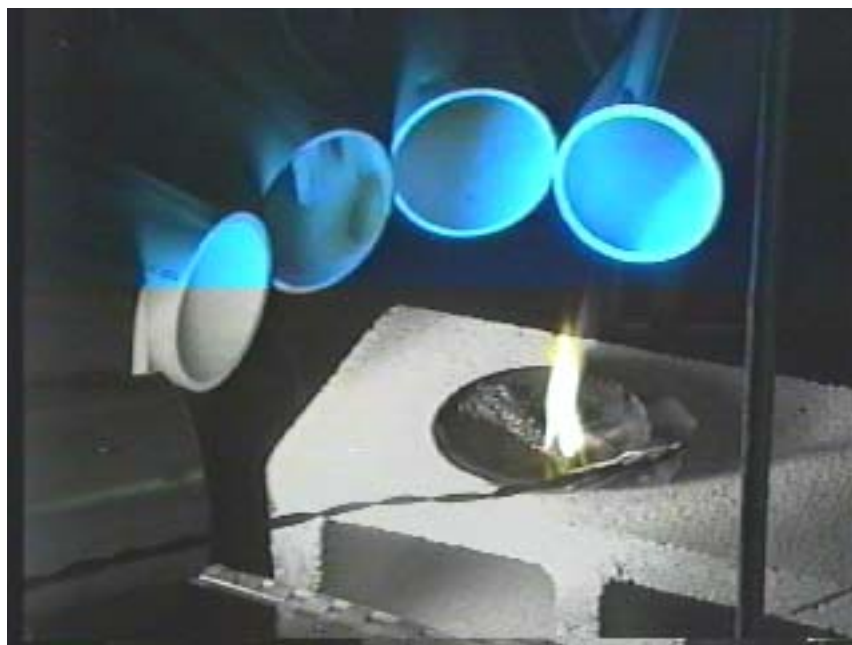


Figure V-3 (b). Extinguishment Sequence, Powder continued

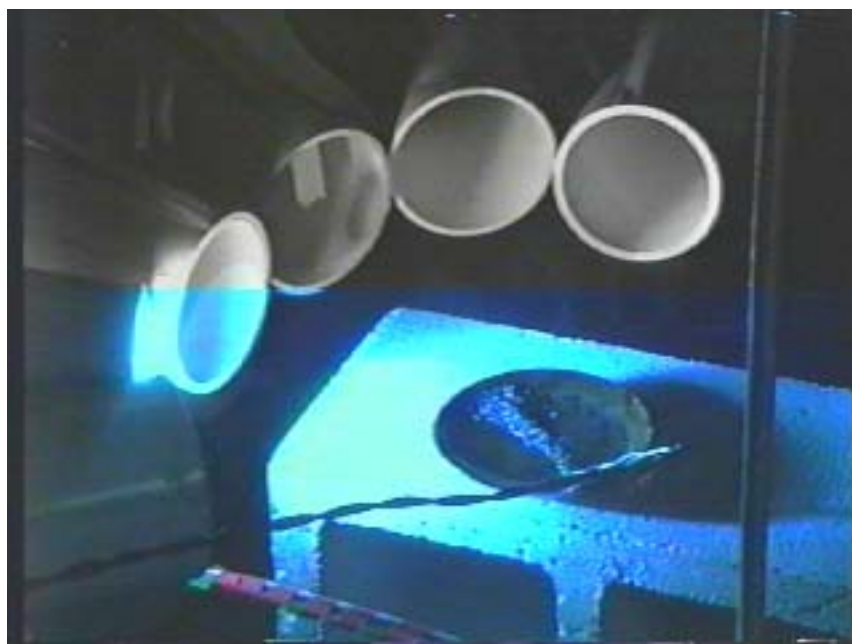


Figure V-3 (c). Extinguishment Sequence, Powder continued



Figure V-3 (d). Extinguishment Sequence, Powder end

4. Operational Experience with the New Device

For purposes of explosion mitigation the intent is obviously to put out a small fire as early as possible. This requires that only a relative small amount of energy should be stored, the consequence being that the pulse rise time becomes shorter. In other words a different device needed to be developed from scratch to deal with explosion mitigation. Experience gained with the original units was very helpful, yet a new device designed for the purpose of explosion mitigation was necessary.

A pressurized spark gap was used instead of the one we were using before. Also the ignitor was replaced with a different design. Pressurized spark gaps are commercially available. We acquired a suitable one. We were successful in reducing the response time from 340 microseconds to 4 microseconds.

A different problem was the modification of the coil. The design philosophy is the interruption of an ongoing copper arc by electromagnetic forces causing its magnetic field to be interrupted very fast and so giving rise to a fast EM pulse (having a rise time less than 1 microsecond). Unfortunately the interruption event was delayed with respect to the trigger

pulse issued by the ignition unit. Some modification was necessary to reduce this inherent delay to a minimum.

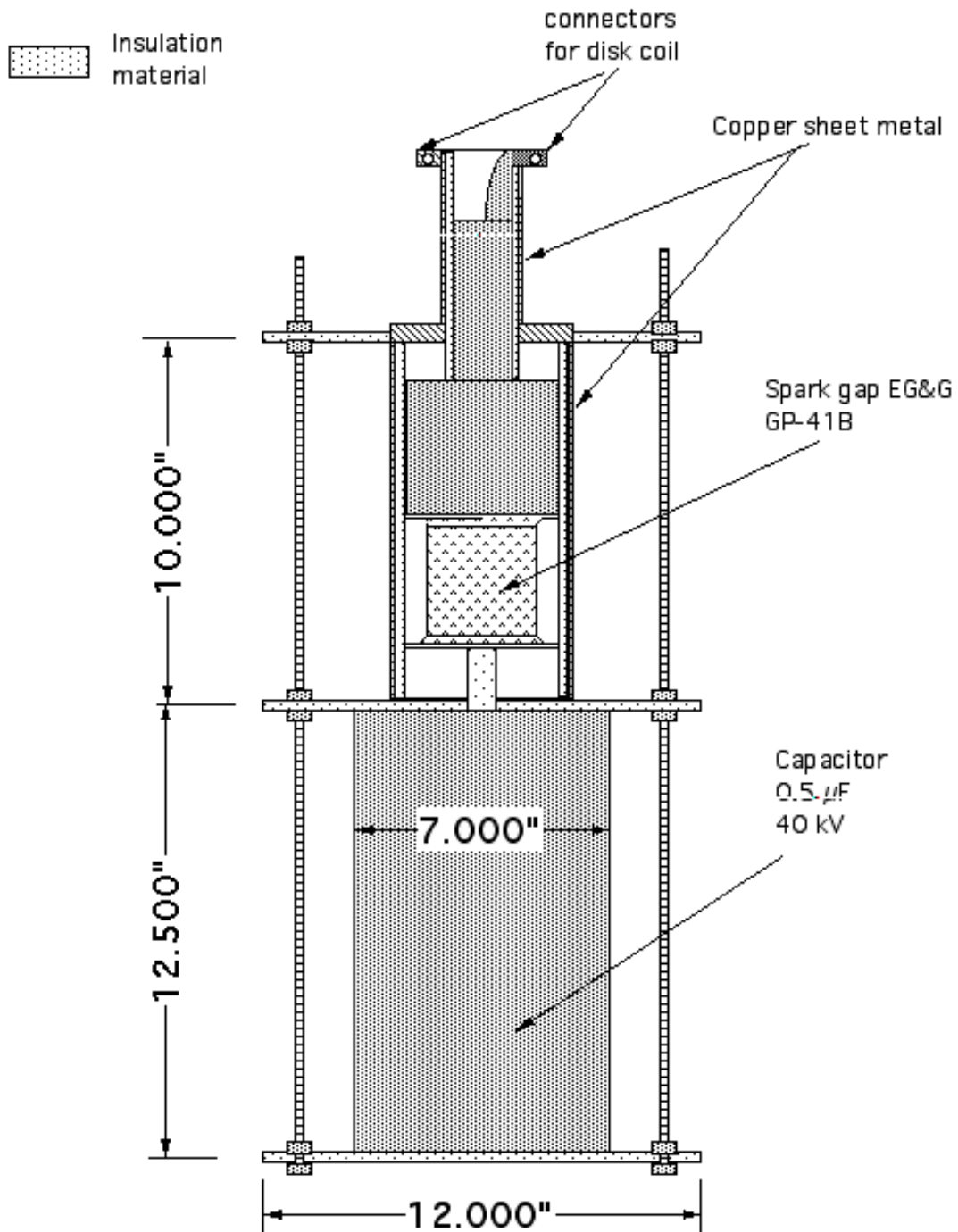


Figure V-4. Schematic Diagram of Prototype

Figure V-4 is a sketch of the redesigned device. The individual units are annotated. The physical dimension are approximate. The electronic units

operating this device are the same as used in the above described experiments. All circuit diagrams can be found in “Appendix A.”

Figure V-5 shows the light intensity of the powder burn vs. time, using the new device. The time between detection and issue of the firing signal was delayed purposely by 10 microseconds to allow the flame to achieve a substantial size. As can be seen in the figure, the burn was extinguished but re-ignited about 30 milliseconds later.

The new unit is only capable of one shot. Therefore, if multiple shots are desired the original units need to be used. As long as the smokeless gun powder is investigated the original units are fast enough. For investigation involving faster burning materials the new units will extinguish the burn in time. If the re-ignition can not be ignored, a new unit capable of multiple firings needs to be built.

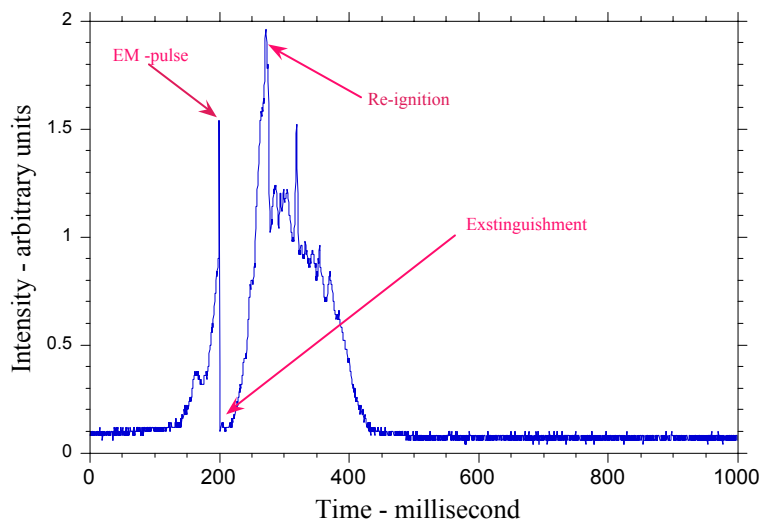


Figure V-5. Intensity vs. Time of Powder Burn

5. Concluding Remarks

Explosion mitigation can not be studied in a laboratory. It rather needs to be done on a range that is equipped for this type of work. The present experiment yielded valuable information for planning explosion studies on a range. It is designed in a way that it can be easily modified to perform on the range for explosion studies. This modification will consist of inserting a long bundle of coax cables between the coil and the device. In case the experiment on the range goes wrong only the coil and a part of the coax cable is destroyed but not the device itself.

Section VI. Extinguishment Mechanism

1. Introductory Remarks

Understanding the mechanism by which the EM pulse extinguishes the flame is of utmost importance for arriving at the best design for the device. The present effort was not a basic research effort but a development effort for the simple reason that at the time the proposal was made it was known that the effect exists, but there was no certainty that the effect was scaleable. Obviously one wanted to know if there is a chance for a viable product rather than expend a large effort on basic research for a product that may never become viable.

Therefore, for the present effort it was necessary to design a well-performing device without a complete understanding of the basic process. Of course in such a situation one tries to guess what the mechanism might be and let the experiment tell the story. This is not a new approach, most all new developments in technology were done this way.

2. A Preliminary Opinion

In the following we discuss our opinion as to what the extinguishment mechanism is, without offering proof for it other than the fact that the device indeed extinguishes fires.

In the following possible extinguishment mechanisms are listed:

a. The *electric field* interacts with the free electrons present in the flame proper, multiplies these by accelerating them along the field lines and by so doing causes additional ionization. The new species formed in this process will radiate more than the flame originally did and so dispose of the freed reaction energy rather than being an energy source for endothermic steps to keep the chain reaction going.

b. The light produced by the discharge interacts with the flame via photo- excitation and photo-ionization and so causes a low temperature

plasma to be formed, one that supports reactions other than the flame originally supported and most of these reactions lead to radiation.

c. The discharge resembles lightning and a sound wave or shock wave, being similar to thunder, is emitted. This wave extinguishes the flame.

d. The discharge causes an air puff, by heating the surrounding air explosively. This air puff blows the flame away from its fuel source and combustion consequently ceases.

e. The magnetic field interferes with the combustion reaction via the paramagnetism of molecular oxygen.

f. Other mechanisms that are not obvious exist.

We will now discuss the experimental evidence that exists in support of one or more of the above mechanisms. Heuristically one would assume that more than one of these mechanisms is involved.

There is also a large body of literature that deals with interactions of external forces (electric and magnetic fields, photo effect, shock waves, etc.). We will cite those references that may shed some light on our situation.

An effect of the *electric field* (case 1 above) on flames is known to exist. Most that are reported in the literature pertain to electrostatic fields. In order to cause additional ionization the field strength should be sufficiently high so that an electron can pick up sufficient energy within one mean free path to cause at least excitation. To deliver such a large field to the flame in the form of an electrostatic field will be very difficult. However, in the form of an electromagnetic wave this may be possible. In this case the electric field appears inside the flame proper. Also, by generation of a wave packet (EM pulse) a larger electric field can be generated and delivered than possible by electrostatic fields.

The disk coil forms a copper arc in the gap that exists in it. The plasma of the copper arc is thrown out of the gap by $j \times B$ forces. This has two effects. The intended effect is that a large current (tens of kiloamperes) flowing inside the coil is interrupted with a rise time of 100 nanoseconds that creates a large *electric field*. An additional effect is that a plasma exists at least nearby the flame. The average temperature of this plasma is in the

order of 20,000 K. For a plasma this is a low temperature, but high enough to prohibit the formation of complex molecules. It is not known how deeply this plasma penetrates into the flame. In principle one could place the coil close enough to the flame that penetration is ensured. However, this was not done and was also not necessary to achieve flame extinguishment. Distances between the coil and the flame were as large as 40 cm.

In order to claim that a modification of the branching ratios takes place leading to an increase in radiation, a necessary observation would be that the flame increases in luminosity prior to extinguishment. Since this is a short-time phenomenon, it is difficult to verify. The reason is that there is a large light phenomenon generated by the interruption of the arc. This phenomenon is about a million times brighter than the intensity of the pool fire. Therefore one would have to measure a small change in intensity on top of a larger intensity.

However attempts were made to trace the intensity of a Bunsen burner (propane) flame through the extinguishment process. This experiment is described in "Section IV Other Observations." It indicates that the flame is immediately extinguished after the EM pulse is over. However, in this experiment the flame is re-ignited shortly thereafter by the hot salt crystal attached to the burner and is extinguished again, possibly by the arriving sound or shock wave.

. Whether *light alone (case 2 above)* extinguishes the flame is questionable. The light emitted by the plasma is indeed very bright, but not concentrated into a beam and focused to a point like in the case of our laser experiment. Light might aid in the extinguishment by photo-excitation and even photo-ionization. But its contribution would need to be studied with more sophisticated experiments that are beyond the realm of the present effort.

However, in a separate experiment we extinguished a small heptane pool flame with a pulsed neodymium-YAG laser. Therefore one can argue that in this case extinguishment was caused by light. The mechanism however is special and does not seem to depend on the wavelength of the laser used. In the classical model of the phenomenon "laser spark" one argues that the electric vector of the light wave is strong enough to break

down the air and to form an air plasma. This would mean that extinguishment is caused by the electric field.

The next mechanism to consider is a *shock or sound wave (case 3 above)*. The experiment described in “Section IV. Other Observations” shows that the flame is extinguished immediately after the EM pulse is over; however, the flame is restarted by the hot salt bar. After some time passes the flame is extinguished again. Before it is extinguished the flame intensity increases, which could be caused by the arriving sound wave when the compression part of the wave increases the air density. It maybe that the subsequent rarefaction wave and the resulting lower air density is sufficient to stop the combustion. The velocity of this wave is either transonic or slightly supersonic; its frequency is 8 kHz. Whether or not the sound wave could extinguish the flame by itself is not entirely clear. The reason is, as pointed out in “Section IV. Other Observations” that the flame was unstable at the time the sound wave arrived. Also the flame under question was a Bunsen burner, rather than one of the larger heptane pool flames that were extinguished with the EM pulse. Therefore, the question of whether the sound wave participated in the extinguishment of the pool flame is still wide open.

The next possible mechanism is the *air puff (case 4 above)*. Also in “Section IV Other Observations” an experiment is described where a piece of paper was inserted between the disk coil and the flame. In this case the flame was still extinguished. This rules out the air puff but not the sound wave.

Another mechanism might be a contribution of the *magnetic field (case 5 above)*. There is no easy way to study its contribution. If electrons need to be affected by an external magnetic field then an eddy current should form. This current would need to influence the chemical reaction in some way. This is not very likely, since it is a macroscopic phenomenon. Of course, there is a microscopic effect via the Zeeman effect. It causes degenerated states to split into their components; however, this does not necessary mean increased emission of light.

There is of course the fact that O_2 is paramagnetic. This means that oxygen could be forced out of the flame proper by a magnetic field gradient. Although the magnetic field externally applied by the EM pulse is large and

inhomogeneous, it is also short lived. Forcing O₂ out of the flame proper is a diffusion phenomenon that is therefore slow. For this reason we believe that this is not applicable to our case.

Summarizing the statements made above, we express the opinion that a reasonable explanation, based on the various side experiments, is as follows. There is an interaction of the electric field part of the EM pulse with the flame. The flame becomes brighter as a result. The increase in brightness indicates the branching ratios of the reactions are being changed in favor of radiation (visual and IR). The flame dissipates the freed chemical energy more by radiation than being a source of energy for the endothermic steps in the combustion mechanism. **In other words the flame is extinguished by radiation cooling.**

Section VII. Comparison to Other Experiments

Research concerning fire extinguishment is almost as old as combustion research itself. Naturally there is a large body of knowledge accumulated over the years. However, we did not find any research that matches our situation closely. Since our effort was a development effort rather than a basic research study, we should not be required to review the entire body of knowledge here. We rather will point out some references that might shed some light on our situation

The Air Force Engineering & Service Center, Engineering & Service Laboratory, Tyndall Air Force Base, FL 32403 commissioned a review study by Jonas and Steel (Ref. 1) covering the literature through 1990. It is reasonable to assume that the major developments are covered and agreed upon by the majority of the researchers. Therefore, we will make only a few comments on the period before 1990 and fill in what seems to be important for our situation past 1990.

The study referenced above contains a table that is useful for an overview and this table is reproduced below as Table VII-1. A few comments will suffice:

In 1999 fires were indeed extinguished by *lasers*, (this report). As pointed out above, it is our opinion that the extinguishment mechanism employs the electric field vector of the light radiation. We used a neodymium-YAG laser. However, it seems that the wavelength of the light is not a major factor. The important point is that the laser must be able to cause a breakdown of the flame environment or the air close to the flame. Since the laser beam must be focused to a point by a lens, it seems to be impracticable to use lasers for extinguishment of larger fires. Therefore, the comment “negative” in the table may as well stand.

Next the *air blast* may be considered by some to be close to our situation. However, we do not believe this. The word “air blast” infers that there is some air movement that displaces the flame from its fuel. In our case the fire is extinguished during the first 10 microseconds (meaning as long as an electromagnetic field is still present). The air movement will be subsonic and will take longer than this time interval to arrive at the location of the

fire. The practice of extinguishing oil well fires with explosives may fall under this heading.

Energy Field	Effect on Fire Extinguishment	Remarks
Electrostatic	Positive	Requires negative space charge
Acoustical	Negative	Tends to accelerate exothermic reactions
Magnetic	Positive	Requires very strong field
Turbulence	Positive	Requires physical coupling to obtain turbulence
Gravitational	Positive	Requires large gravitational field
Charged Particles	Not determined	Forms soot particles
Plasma	Negative	Enhances flame
Air Blast	Positive	Blows out flame
Lasers modulation	Negative	Causes ignition or used for diagnostics, however, frequency might induce flame instability
Microwave	Negative	Ignites and sustains a flame, modulation might induce flame instability

Table VII-1. ENERGY FIELD EFFECTS ON FIRE EXTINGUISHMENT (Ref. 1)

Also in the table the heading *plasma* may be not entirely negative. It is true that a flame can be ignited by a plasma, but once the plasma is established and the flame is engulfed by it, the chemistry changes drastically. Combustion reactions of the low temperature environment “flame” are replaced by dissociation, excitation and ionization. Even in a low temperature plasma (20,000 K) amongst the different species of particles, molecules are a minority. Under these conditions any solid or liquid fuel acts as a heat sink and the plasma needs to be maintained by external means. One may wonder if the fire restarts once the external energy source that created the plasma is removed. Whether or not this happens might depend on the circumstances. In our situation the flame is not engulfed by the plasma. It is far enough away to prevent a re-ignition by the decaying plasma. In some cases we indeed do have re-ignition, but that happens much later--after the decaying of the plasma has taken place. Therefore, again a plasma by itself is not necessarily a practical way to extinguish fires, but new ideas may come up in the future that involve plasmas.

Microwave in combination with a plasma may be such a future idea, but for the present effort it has no bearing. In our case the plasma probably does not contribute at all to the extinguishment.

Turbulence, Gravitational Forces and *Charged Particles* do not play a major role in our situation. This leaves Electric Fields, Magnetic Fields and Acoustics to be discussed.

Acoustics was already mentioned as a possible contributor once the flame is destabilized. This was discussed in “Section IV. Other Observations” for the case of the Bunsen burner. There is also a possibility that some role is played by acoustics in the extinguishment of propane flames discussed in “Section III. Operation of Device.”

Magnetic Forces probably do not play a role in our situation, albeit we obtain a large magnetic field during the EM pulse, if we want it or not. At the present time we have no evidence at all that would support a role of the magnetic field. We must rely for this on the literature. We quote Weinberg (Ref. 2) here: “So long as the flame is to be the sole ion source,

the effect of a magnetic field compares with an electric field most unfavorably.”

There are of course other references. Ueno (Ref. 3) talks about a magnetic curtain, which is also called an "air curtain" that blocks air flow in and out of the location containing the flame. The interception of oxygen by the magnetic curtain quenches flames. Wakayama and Sugie (Ref. 4) even observed a promotion of the combustion process when fuel gas flowed in the direction of decreasing field strength. Abe and Hayashi (Ref. 5) states: "These results show that a magnetic field can influence the reaction kinetics in the gas phase, but the detailed mechanism for the observed magnetic field effects remain unknown at present." In contrast to this Chen et al. (Ref. 6) states: "[An]...external applied magnetic field seems [to have] no apparent effect on flame velocity and flame shape.... For pure hydrogen and oxygen flame[s],... increase[s] of H^+ concentration and OH band [intensity] were observed.”

Finally a historic fact should be mentioned namely E. Steubing [*Verh. Dtsch. Physk. Ges.*, 15, 1181 (1913)] discovered the magnetic field quenching of the visible emission from iodine vapor. This could be construed as a modification of the branching ratios.

This leaves *Electric Fields* as possible players in flame extinguishment. This phenomenon was more intensely researched than the others mentioned above. However, most of the time the interest was in promotion of combustion rather than in extinguishment. Nevertheless one should bear in mind that a promotion of the combustion that increase flame velocity can, in the extreme, lead to extinguishment if the free radicals are consumed faster than they can be created. Therefore the following references still shed light on the processes in which we are interested.

Bowser and Weinberg (Ref. 7), Bradley and Nasser (Ref. 8), Grosjean (Ref. 9) fall in this category. They state that electric-field-induced effects alter the flame geometry as well as the flame-blowout limit, increase the flame stability, improve the heat transfer to solid surfaces, increase the burning velocity, and elevate the electron temperatures in the flame. Tewary and Wilson (Ref. 10) also found a marked increase in the propagation rates of methane/air flames by a high frequency electrical field. Jaggars and von Engel (Ref. 11) also observed increase reaction rates caused by electric

fields. They state that “from observations in hf fields, it is concluded that electrons alone are the primary agents.”

On a more positive note Marcum and Ganguly (Ref. 12) found in a diagnostic paper, that investigates the action of an applied electric field on a flame, that the inner core height of the flame is decreased and turbulence sets in. They explain this and other observed effects by the ion drag force due to the charged particles. Inomata et al. (Ref. 13) also looks for flame promotion but finds possible problems: “...it is possible to produce many active species by a silent electric discharge, but, to promote combustion, it is necessary to keep the time interval from production of active species to combustion as short as possible and to ensure that the combustion zone is kept away from the electric field because premature oxidation and field-induced quenching are both counterproductive.”

Fortunately there are also a number of papers where flames actually were extinguished by electrical fields. For example, Sher et al. (Ref. 14) “Extinction of Flames in a Nonuniform Electric Field” and Sher et al. (Ref. 15) “Extinction of Pool Flames by Means of a DC Electric Field”.

In conclusion one might state that it is possible to extinguish flames with magnetic forces, but obviously a better way is to use electric fields. Therefore, based on above evidences we formed the opinion that the extinguishment by an EM pulse is mainly caused by the electric field. However other effects, namely acoustics and turbulence, may play a secondary role as well.

Section VIII. Conclusions and Recommendations

1. Possible Application of the New Technology

We like to believe that the new technology is a step in the right direction. The fact that no extinguishment agent is required should be of considerable value. The only item that needs to be brought to the location of the fire is electrical energy.

It may be the case that electrical energy is available at the location of the fire. In this case only personnel and a few coils (not even capacitors) need to be carried. This would make it possible to use helicopters.

In case there is electrical power generation necessary at the fire location, diesel fuel and a generator need to be carried. Even so, this may be less of a problem than transporting water.

A major question may be whether the new technology can be further scaled up to large fires. Since we put out a flame front of 24 inches, and needed 9 coils for this, this may be an important question. However, this is not the entire story. It required only 3 coils to initially extinguish the flame front; the other coils were used to subdue re-ignition.

Since 9 units and a special unit that is somewhat faster will be turned over to the designated AFB, there is some opportunity to explore scalability farther, requiring only a modest investment.

Basically it is obvious that introduction of such a radically new technology will eventually require major investments. It is hoped that the results of the present Phase II will help to come to such a decision.

2. Recommended Basic Research Follow-up

If there should be intentions to go farther in the development of the new technology, then it would be most advisable to one or more basic research studies that determines the extinguishment mechanism(s) perform

along with such a development effort. Of course that will help to keep the development effort on the right track.

What should be studied is:

a. The time history of the extinguishment, especially the first 100 nanoseconds.

b. What new species are formed during this initial time by the application of the EM pulse.

c. What causes the re-ignition; and, in this context, what type of particles are contained in the clouds that hover over the fuel supply without touching it.

d. Based on the results of the above listed studies one needs to come to a conclusion whether the EM pulse creates a chemical extinguishment agent or if the electric field rearranges the branching ratios so that extinguishment occurs due to radiation cooling.

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Appendix A. Circuit Diagrams

1. Ignitor Circuit Operation

The ignitor circuit, dwg. 99-110, translates an optical pulse signal from the input fiber into the initiation of the main discharge. This is accomplished in the following manner. A Hewlett Packard high-speed receiver module, HFBR-2521, detects the light pulse with a PIN diode and amplifier combination. The amplifier output is by high-speed schottky architecture and drives two stages of n channel FET's, the second of which triggers an SCR acting as the main switch in the ignitor primary loop. With no light the receiver output, pins 1,4 and the gate of the 2N7000, are in a high state. Thus the channel of the 2N7000 is conducting and the gate of the F840LC is at ground potential, or approximately the same voltage as its source (S pin). The leading edge of the light pulse causes a falling output voltage at pins 1,4 of the receiver, and hence a shutoff of the 2N7000. This in turn raises the gate potential of the F840LC to near the supply level, and turns it on permitting current flow into the gate of the BT152-800R, thus turning it on. Two 33-mH inductors and a 51-ohm resistor in the supply and ground leads, along with the 5-volt zener across the receiver module supply leads, form a protection system to isolate the receiver module from spurious pulses which may propagate backward from the main discharge system during firing.

From the circuit diagram it is clear that the ignitor circuit is powered by batteries. Two separate packs are used. A four cell system giving 6.25 volts is used for the receiver side of the ignitor. The other pack, comprised of three cells giving 4.6 volts, is used to charge the primary ignitor capacitor. This capacitor, 3.5 to 4.5 microfarad oil-filled, is charged to approximately 500 volts. We utilized a photoflash high voltage switching supply from inexpensive flash units. This approach was less expensive and quicker than constructing the high voltage converter ourselves.

Energy stored in this capacitor is dumped into the primary connection of an automobile ignition coil when the SCR switch, BT152-800R, is activated. This then produces a pulse approaching 20 kV in the main discharge unit spark gap, thus initiating the main discharge action. Delays in this system are minimal and were measured at several microseconds. On the

other hand major delays were seen in establishment of current flow in the main spark gap switch. These could be on the order of two to three hundred milliseconds.

2. Main Discharge Power Supply

Drawings 99-120 and 99-121 illustrate the charging circuit and control respectively for the main capacitor. A 120 volt line supplies power to the primary of an isolation transformer as well as to a plug-in wall power supply (12 volts DC out). The secondary of the isolation transformer is around 90 volts and connects to the primary of a 15 kV neon sign transformer. This connection is made through two relays which switch the neon transformer on and off to regulate the required voltage across the main capacitor. These relays also switch red and amber LED strips on and off to indicate the current state of the main capacitor charging cycle. Control of these relays is by the high voltage level control and safety charging control circuitry on the controller board.

Output of the high voltage transformer is rectified by a full wave bridge comprised of two high voltage diodes per leg (type TCG542) to prevent premature failures due to spurious currents during discharge. Output of this bridge is directed to the main capacitor through RL snubbers on both positive and negative leads. These minimize damaging effects of backward propagating pulses from the discharge system. A divider comprised of a 1090 megaohm resistor in series with a 250k potentiometer is also connected across the capacitor and used by the controller board to sample capacitor voltage for regulation.

A safety measure included in this system is a discharge/activate handle that is placed in one of two positions depending upon the action desired (seen in both 99-120 and 99-121). It is plugged in across the main capacitor to make the unit safe for antenna replacement or work on the main trigger gap or transmission rails. Before the unit will charge the main capacitor, the handle must be removed from the main capacitor position and placed in the charging position, effectively arming the power supply. The two positions are physically in separate locations and the position of the handle gives a good visual indication of the operational state of the unit.

Drawing 99-121 details the power supply controller board. This board contains two sensing circuits with relay drivers and relays. Each circuit uses a MAX931 comparator as a level sensor and a 2N7000 to drive the relay coil. One circuit monitors the voltage on the main capacitor, turning power to the neon transformer primary on and off with the relay accordingly to keep the capacitor voltage at the desired charge level. This is the top circuit on the diagram of the board. Note that its relay also controls the amber and red LED strips as an indication of the charging state. The lower circuit detects the presence of the Safety Handle, which must be plugged into the charge position to activate its relay and permit charging to occur. Discharge location of the Safety Handle is also indicated in the upper circuit. Power for the comparators and relays is supplied by a small wall plug in transformer capable of 300 mA at 12 volts. These are lightly filtered and supply about 15-16 volts with minimal load. It was chosen to operate the MAX931's at 5 volts, hence the 1N5240 in the supply to the IC's.

3. Master Trigger

The master trigger unit, drawings 99-130 and 99-131, is designed for and used to trigger one to ten discharge units with widely varying delays after the initiating event. This is accomplished by generating a pulse train of adjustable frequency which is directed into the shift clock and store clock inputs of two cascaded 16 bit shift registers. Initialization of a shifting wave through the 32 bits of the shift registers is accomplished by pulling the serial data input line of the lower word chip high with the fire switch. The high-going pulse ripples through the shift registers from least significant bit to most significant bit. Delay of this wave between output lines is dependent on the clock frequency. These connections can be seen along the top of Dwg. 99-131.

The high thirty of the thirty two output lines of the two 74F675A shift registers constitute the "trigger signal bus" as indicated in the drawing. This bus feeds a bank of 10, thirty bit switches which permit the selection of one of the thirty trigger signal bus lines for each of the output channels. Selection of one of these lines determines the delay of the fire signal (number of steps through the shift registers at the selected clock rate) which reaches the respective one of ten optical output drive modules HFBR-1521. The lower half of Dwg. 99-131 shows this connection from the bus, through

the selection switch, to the DS75451 peripheral driver, and then the fiber optic module. It will be noticed that channel one also has a one-shot, triggered off the channel one delayed signal, and directed to a scope trigger output. This pulse is nominally one millisecond in length.

Power for this trigger box is supplied from a 12 volt lead acid battery connected to a power input plug. This voltage is immediately reduced to 6 and 5 volts with appropriate 3 terminal regulators. It should be noticed that the clock and the one-shot are both implemented with surface mount devices, MIC1557 and MIC1555, on SURF boards. These boards are then wired directly into the prototype boards for the rest of the master trigger unit. Clock rates were initially set such that pulse to pulse delays were 1, 5, 10, 50, and 100 microseconds selectable by the master oscillator switch. For later studies these delays were increased by a factor of 10, (or the clock rates were divided by 10).

4. Detonation Mitigation Trigger

In order to test the effectiveness of the EM pulse in mitigating an incipient explosive process we needed a fast detector-trigger system that would trigger an EM unit when the light from a burning powder was detected. To accomplish this one of the optical detectors that had been used throughout these experiments was modified to do the job. Drawing 99-100 shows the diagram of how this was done.

Optical pulse detectors were made using either IR or UV sensitive detector diodes and the circuits were essentially the same as that shown in the upper left of the drawing. Power was supplied by two 9 volt batteries as illustrated in the bottom left. To modify one of the IR detectors, a high speed comparator was used to compare the detector output voltage with a reference supplied by the 250 k potentiometer. When switched to internal threshold the output of this comparator, buffered by the 2N7000, drives the HFBR-1521 fiber optic output module. The threshold can be adjusted to respond when the optical detector signal is still small, or when it is large, thereby controlling the delay through the unit somewhat. The fiber optic output is then connected to the ignitor of the EM discharge unit. Note the input to the 2N7000 also drives a second comparator which will act as a driver for an

analog output line. In our unit this output has not been connected although the comparator is wired up.

To make this trigger unit even more versatile, the optical detector output is directed to a BNC and can be used to trigger an external Wavetek pulse generator. This generator can be set with precise variable delay. Its output pulse is then fed into the external pulse input and switched to the FET driver for the fiber optic module.



See the following pages for the
drawings mentioned above.

